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The main objective of this project was to acquire laboratory equipment developed under the Strategic Highway Research Program (SHRP). The use of the facility is geared towards 1) understanding the pertinence and importance of different rheological parameters of traditional paving and other recyclable materials as related to performance-based design procedures and 2) performing basic research to understand the constitutive models related to viscoelastic, dynamic and nonlinear behavior of these materials. A upper-division course entitled "Pavement Materials Characterization" is using the equipment as a teaching tool. Two research projects funded by the Texas Department of Transportation and Federal Highway Administration have also been extensively using the facility.

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Abstract

The main objective of this project is to acquire laboratory equipment developed under the Strategic Highway Research Program (SHRP). The use of the facility is geared towards 1) understanding the pertinence and importance of different rheological parameters of traditional paving and other recyclable materials, as related to performance-based design procedures and 2) performing basic research to understand the constitutive models related to viscoelastic, dynamic and nonlinear behavior of these materials.

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Chapter 1

Introduction

State and federal regulatory agencies are mandating the reuse of reclaimed paving materials, as well as, other environmentally undesirable waste in the construction or rehabilitation of pavements. The state-of-practice in design of pavements is empirical, thus utilizes very little information related to the performance-based parameters of the pavement layers. The need for the development of rational design methodologies, which implies that the fundamental properties of these materials have to be well-understood, has been recently greatly emphasized. The equipment required to carry out this task has only recently become available mainly through efforts in the Strategic Highway Research Program (SHRP). Under this contract, a facility was developed to perform test procedures and design methodologies suggested by SHRP.

The major instrumentation requested are several devices, that can be utilized to measure fundamental stiffness and rheological properties of paving materials. Equipment specifically requested are in the following areas:

1.   the preparation and conditioning of asphalt binders and asphalt stabilized materials,
2.   the rheological characterization of asphalt binders, and
3.   the determination of stiffness parameters of asphalt mixtures.

Objectives

The main objective of this project is to acquire laboratory equipment developed under the Strategic Highway Research Program (SHRP). The use of the facility is geared towards the following items:

1.   understanding the pertinence and importance of different rheological parameters of traditional paving and other recyclable materials, as related to performance-based design procedures, and

2.   performing basic research to understand the constitutive models related to viscoelastic, dynamic and nonlinear behavior of these materials.

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The use of the new facility is directly related to the retrofitting of America's infrastructure, the reuse and reduction of waste-two major civilian and defense related goals in the post cold war era. The facility, which is used and managed by the Center for Geotechnical and Highway Material Research, is being utilized to conduct competitive research, and to educate a large number of minority students in the area.

Organization

Since all funds allocated to this project are solely for acquiring equipment, it is not possible to provide a traditional and highly technical report. The equipment purchased and their benefits are described in Chapter 2. Chapter 3 contains a brief summary of the educational and research-related use of the facility. Two appendices are included, which provide more information on the ongoing project.

Chapter 2

Description of Facility

As a result of the recommendations put forward by SHRP projects, changes in laboratory tests and equipment are being implemented in the paving industry. In the near future, engineering practice will be gradually shifting into the new methodologies and will completely convert to the new standards. However, the training of future pavement engineers, as well as, research on new potential materials should be converted into the new methodologies at a much earlier stage.

In this sense, it is clear these changes will have to occur much faster in the university environment. This sudden change requires the elimination of obsolete equipment and the purchase and installation of updated test equipment. The equipment purchased under this grant can be grouped into four major categories. The first group is related to laboratory methods to condition or age specimens of bituminous binders in order to simulate such field processes during the construction or pavement life.

The second group consists of equipment for the rheological characterization of asphalt binders to provide properties, which are related to mix performance. This is probably one of the aspects that has changed more drastically as a result of SHRP. The major tests focus is to provide properties which are related to the workability of the mix, and to the selection of binders appropriate to resist rutting, fatigue and low-temperature cracking.

The third group of equipment consists of the required methods to compact specimens of asphalt mixes. The main equipment in this group is the Gyratory compactor. The main purpose of this test is to duplicate in the laboratory the compaction effected by the traffic loads in the field, thus producing specimens of asphalt concrete more representative of the field materials.

The last group consists of the equipment necessary to test asphalt concrete mixes, for such applications as measuring the moduli or determining resistance to stripping.

In addition, to the advanced devices purchased under this grant, a significant upgrading of the conventional equipment has also been carried out using matching funds provided by UTEP.

Binder Aging Equipment

Asphalt binders age during mixing of asphalt and aggregate (a.k.a. short term aging), as well as, due to reaction with oxygen from the environment (a.k.a. long term aging). Binder aging equipments are necessary to simulate both short term and long term aging in the laboratory. The equipment purchased under this category are Rolling Thin Film Oven, (for simulating short term aging) and Pressure Aging Vessel (for simulating long term aging).

Rolling Thin Film Oven (RTFO). The aging of asphalt binder during mix producing and construction is simulated by aging the binder in a RTFO, as shown in Figure 2.1. This test exposes a film of binder to heat and air, which approximates the exposure of asphalt to these elements during hot mixing and handling. The equipment uses 350 gm of asphalt binder, $163\pm 0.5°C$ temperature, and air flow of 4000 ± 200 ml/min to simulate the aging.

Pressure Aging Vessel (PAV), as shown in Figure 2.2, is a pressure vessel which is placed in a temperature-controlled chamber. About 50 gr of binder is poured in trays that are placed inside the PAV vessel. The vessel is then subjected to a pressure of about 2 MPa for a period of 20 hours. A temperature of about 90 to 110°C is maintained throughout the test.

Binder Characterization Equipment

The binder characterization equipment is necessary for determining the fundamental characteristics of the bituminous binders (i.e., rheological, consistency, aging level, temperature sensitivity among others).

To classify the asphalt binder three items are needed. Each one is described below. A fourth item, direct tension test device, is also necessary occasionally. Even though the item was originally budgeted, it was not purchased, because the consensus of the researchers is that the equipment requires further development.

Bending Beam Rheometer (BBR), as shown in Figure 2.3, is used to measure the low temperature stiffness of the asphalt binder and to calculate the slope of the log stiffness versus log temperature curve. The stiffness is related to the thermal cracking, and the slope is related to low temperature thermal shrinkage cracking, to fatigue resistance of the asphalt binder, and to the overall quality of the binder.

An asphalt beam 125 mm long, 12.5 mm wide and 6 mm thick is prepared. The beam is placed on two supports spaced 100 mm apart. The supports and the loading mechanism are submerged in a cooling liquid. The beam is loaded at its midpoint with a constant load of 100 g, and then the deflection of the midpoint of the beam is measured for about 4 minutes. The stiffness as a function of time is calculated from the measured load and deflection.

High-Temperature Rotational Viscometer is used to measure the steady-state viscosity of asphalt binders at mixing and compaction temperatures. The measurement is used to develop a viscosity-temperature curve.

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Control Switches

Vent

Fan

Window

Bottle With Asphalt

Air Regulator

Air Flow

Bottle

Door

Asphalt (35 +/- 0.1 gm)
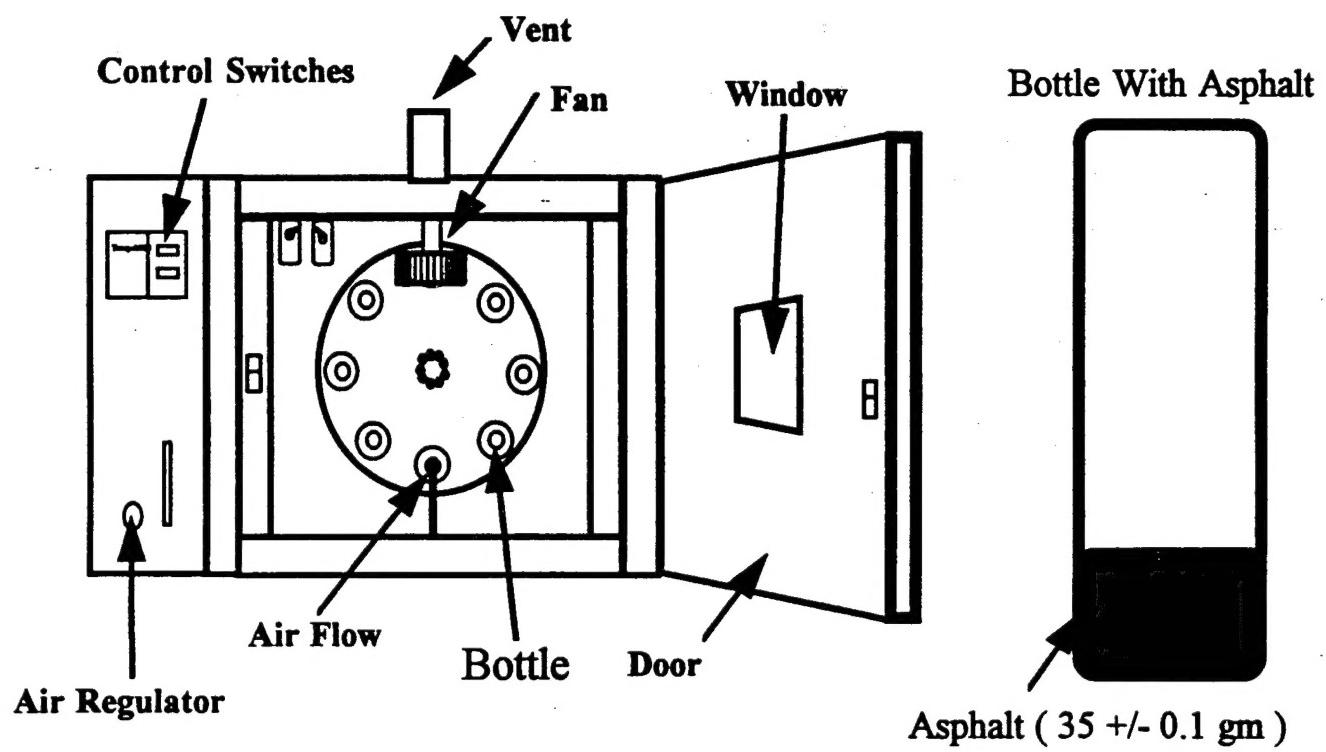
Figure 2.1 - Schematic of Rolling Thin Film Oven

21 bar
(30 psi)

precision oven
at 100⁰ C
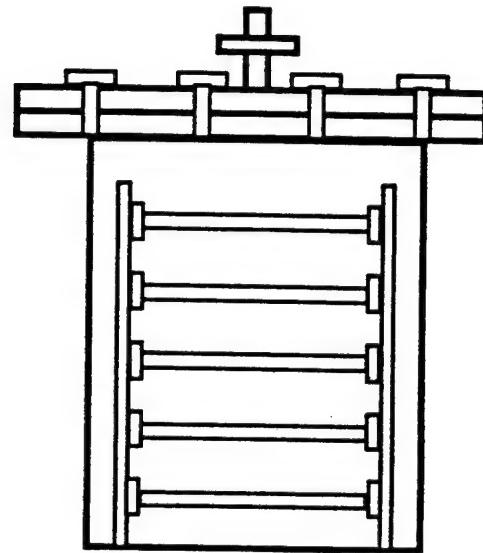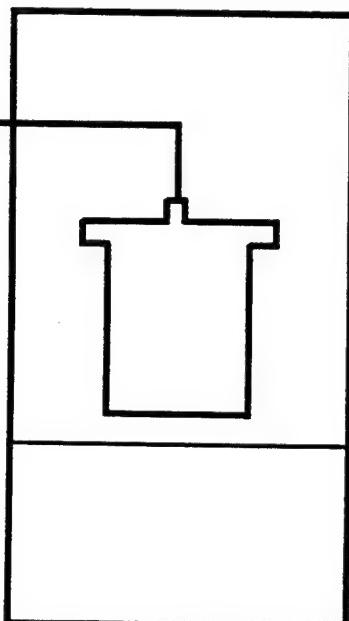
Detail of PAV

- •TFOT aging first
- •Up to 10 pans
- •20 hrs. in vessel

Figure 2.2 - Schematic of Pressure Aging Vessel
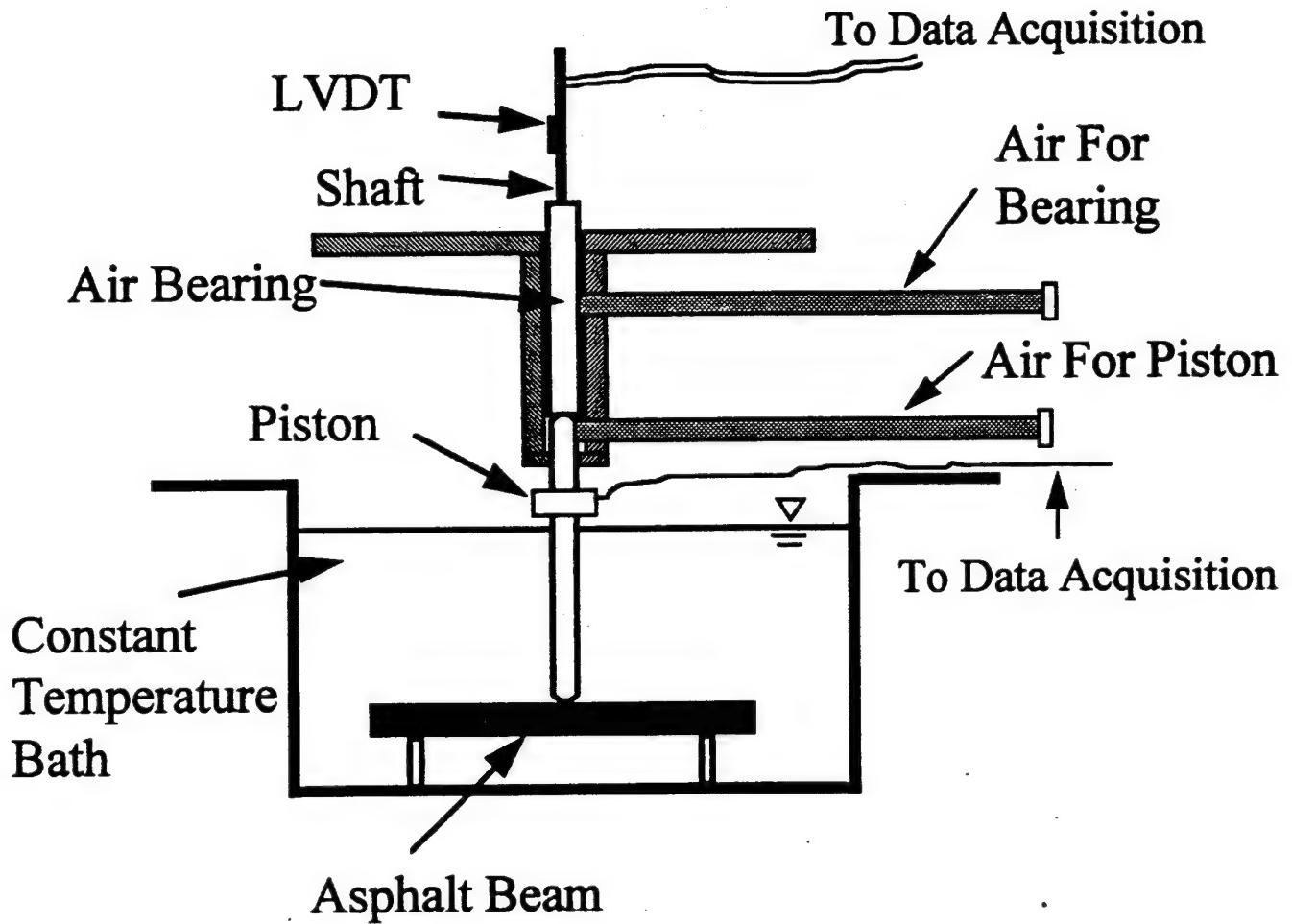
Figure 2.3 - Schematic of Bending Beam Rheometer

To perform the test, preheated asphalt binder is poured into a thermostatically controlled sample chamber (see Figure 2.4). A spindle, which is attached to a rotating shaft, is placed into the specimen. The viscosity is determine based on the resistance to the rotation of the spindle.

Dynamic Shear Rheometer (DSR) is used to measure the linear viscoelastic moduli of asphalt cement binders under a sinusoidal loading mode. The device is particularly useful at the upper range of temperatures where rutting is the primary distress mechanism, and at the intermediate temperatures where fatigue is the primary distress mechanism. Measurements may be obtained at different temperatures, strain and stress levels and tests frequencies. The device may be used to invoke time-temperature superposition and to construct thermorheologically simple linear viscoelastic master curves.

A schematic of the device is shown in Figure 2.5. To perform the test, the asphalt binder is placed between two parallel test plates 8 to 50 mm in diameter, in which the plates are oscillated, the maximum torque, angular deflection, and phase angle are recorded. From these three parameters, the complex modulus is determined.

Specimen Preparation of Asphalt Mixtures

One of the most essential parameters for developing realistic models for asphalt mixtures is the closeness of the specimens prepared in the laboratory with the actual mixtures laid down in the field. SHRP recommends a modified compactor for this task.

SHRP Gyratory Compactor, which is an extension of the Texas gyratory compactor, is modified in several ways (see Figure 2.6). The diameter of the mold is increased to 150 mm to minimize the effects of aggregate top size on the quality of the specimen. The angle and speed of gyration are also optimized to yield more realistic specimen. The load and deformation of the specimen during the compaction are also measured. These parameters can be directly related to the suitability of the mix for effective placement during construction.

Properties of Asphalt Mixtures

Environmental Conditioning System (ECS) has been developed to determine the potential for moisture damage to an asphalt mix. In this testing methodology, a cylindrical specimen 100 mm in diameter by 100 mm in height is subjected to cycles of temperature, to repeated load pulses, and to moisture conditioning.

The schematic of the device is shown in Figure 2.7. The system consists of an environmental-chamber retrofitted with a pneumatic actuator. A servo-valve in conjunction with appropriate hardware and software are utilized to apply repeated loading to the specimen during the conditioning stages, as well as to determine the resilient modulus of the specimen being tested. In addition, the air permeability and hydraulic conductivity of the specimen can be measured using special inlets/outlets contained in the top cap and the bottom cap of the device.

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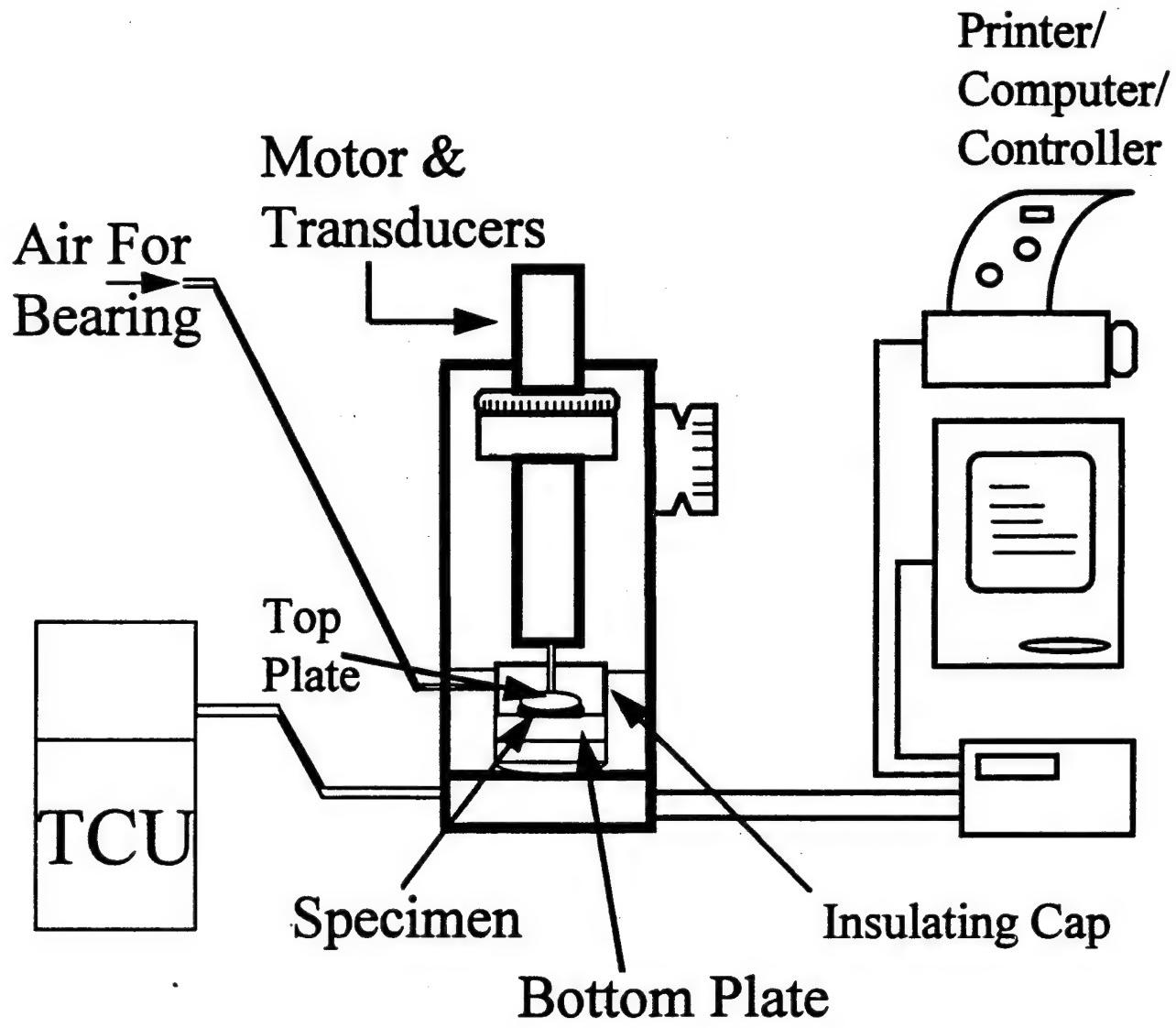
Figure 2.4 - Schematic of High-Temperature Rotational Viscometer
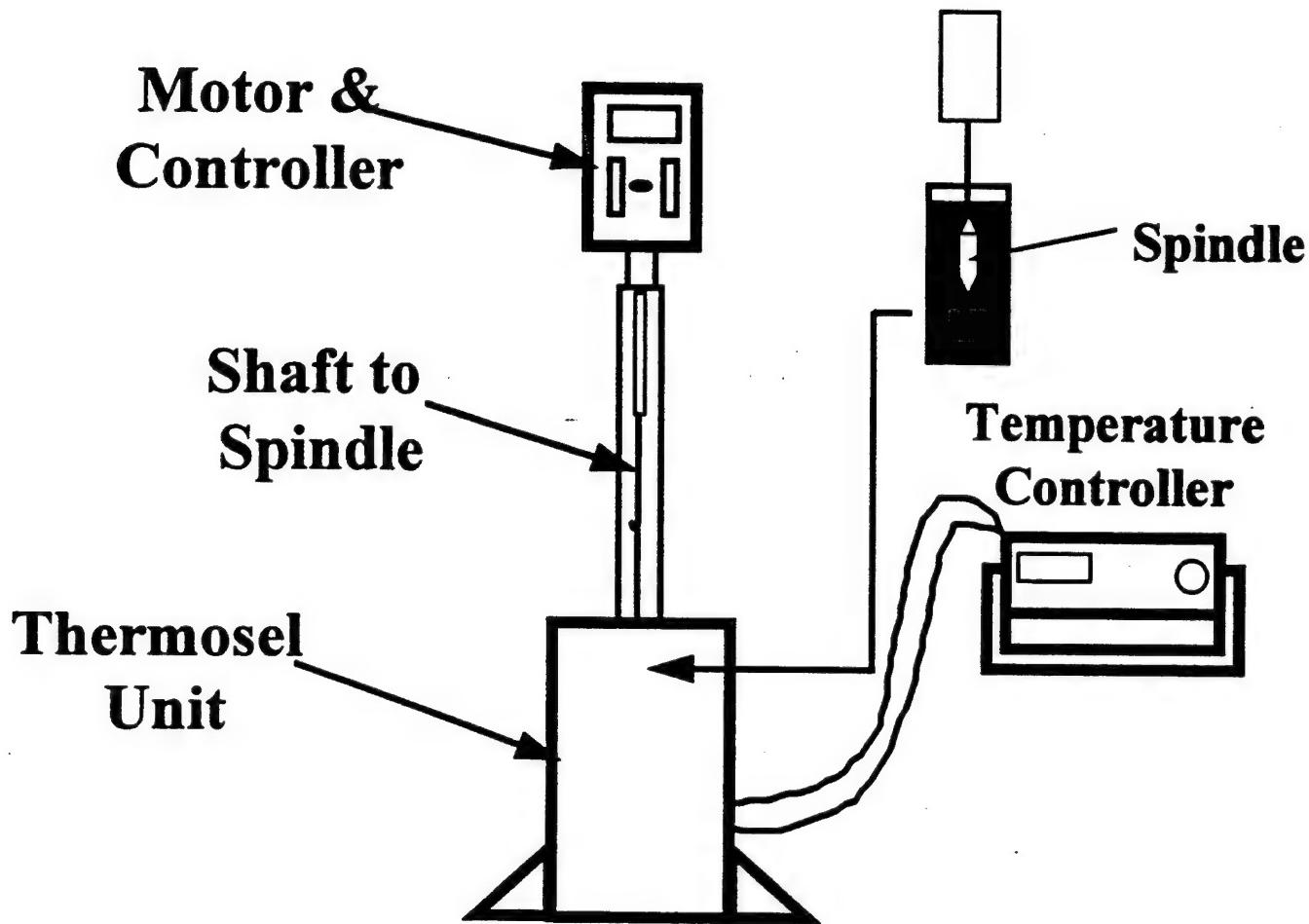
Figure 2.5 - Schematic of Dynamic Shear Rheometer

control and data acquisition panel

reaction frame

loading ram

mold

rotating base
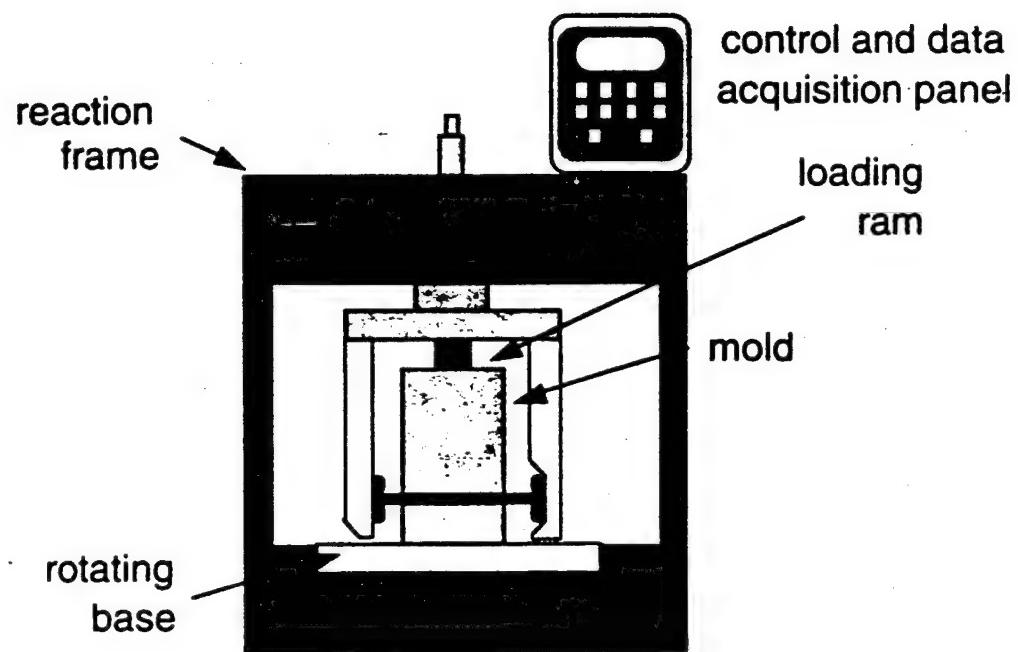
Figure 2.6 - Schematic of SHRP Gyratory Compactor

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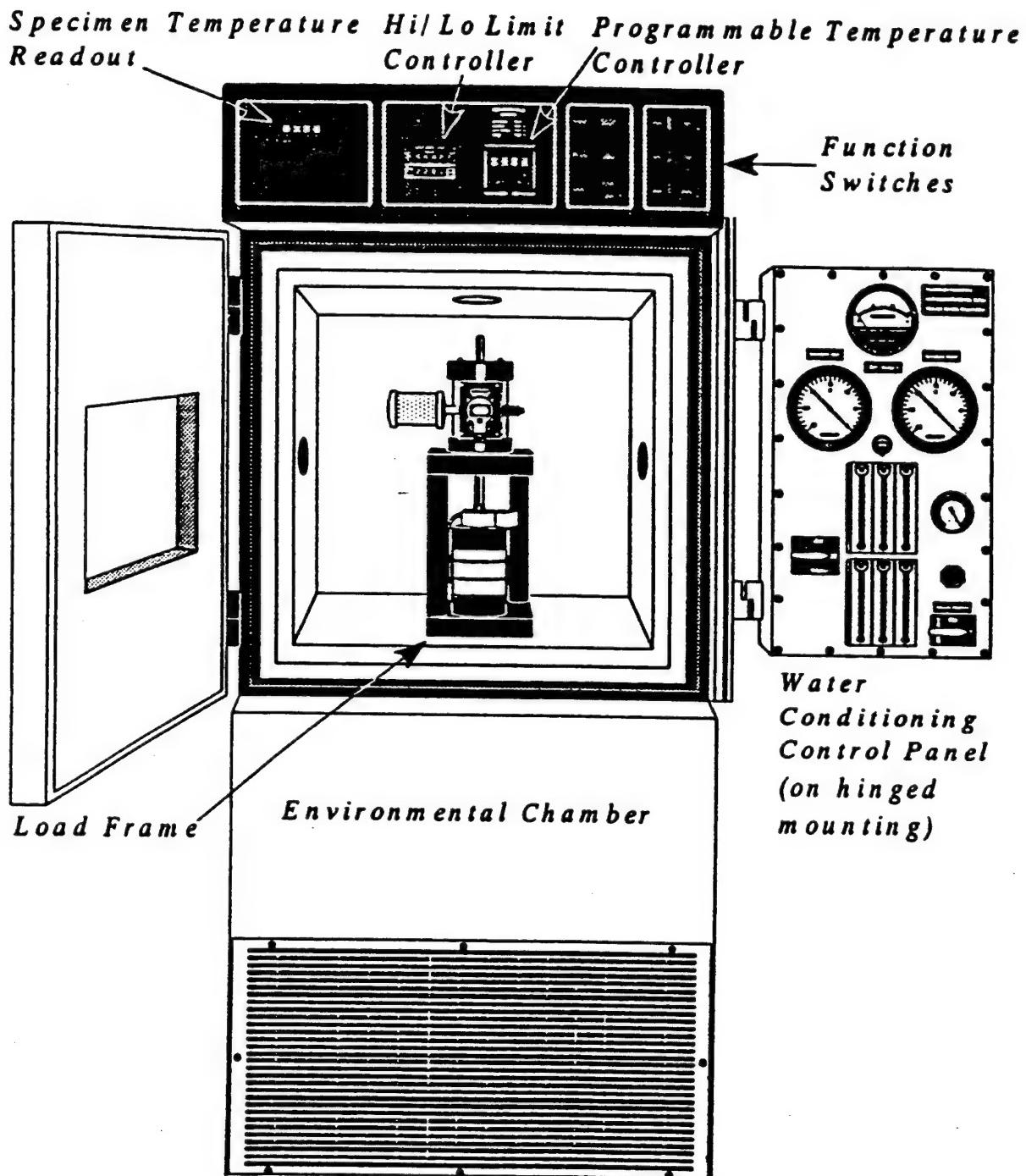
Figure 2.7 - Schematic of Environmental Conditioning System

The procedure for interpreting the results is still tentative, therefore it has not been finalized. The most recent specification requires the modulus ratio to be greater than 0.70, after the completion of the final conditioning cycle.

Indirect Tensile Creep and Strength Tests are the major tests used to predict the behavior of asphalt mixes. The two common modes of these tests are indirect tensile tests on standard brikettes and the unconfined compressive tests on 100 mm by 100 mm specimens.

Tests can be performed in three modes — static strength tests, dynamic repeated loading tests, and creep tests. To perform these tests we have acquired an MTS servo-valve dynamic testing system, and we are developing the required attachments, so that these tests can be readily performed.

Thermal Stress Restrained Specimen Test (TSRST) is designed to evaluate the low temperature cracking characteristics of asphalt concrete mixtures. The test equipment simulates field conditions by cooling a specimen, while restraining it from contracting. When the tensile stress equals the tensile strength of the specimen, the specimen fractures.

As shown in Figure 2.8, the test equipment is comprised of three subsystems: a cooling system, a load/displacement system, and a test control/data acquisition system.
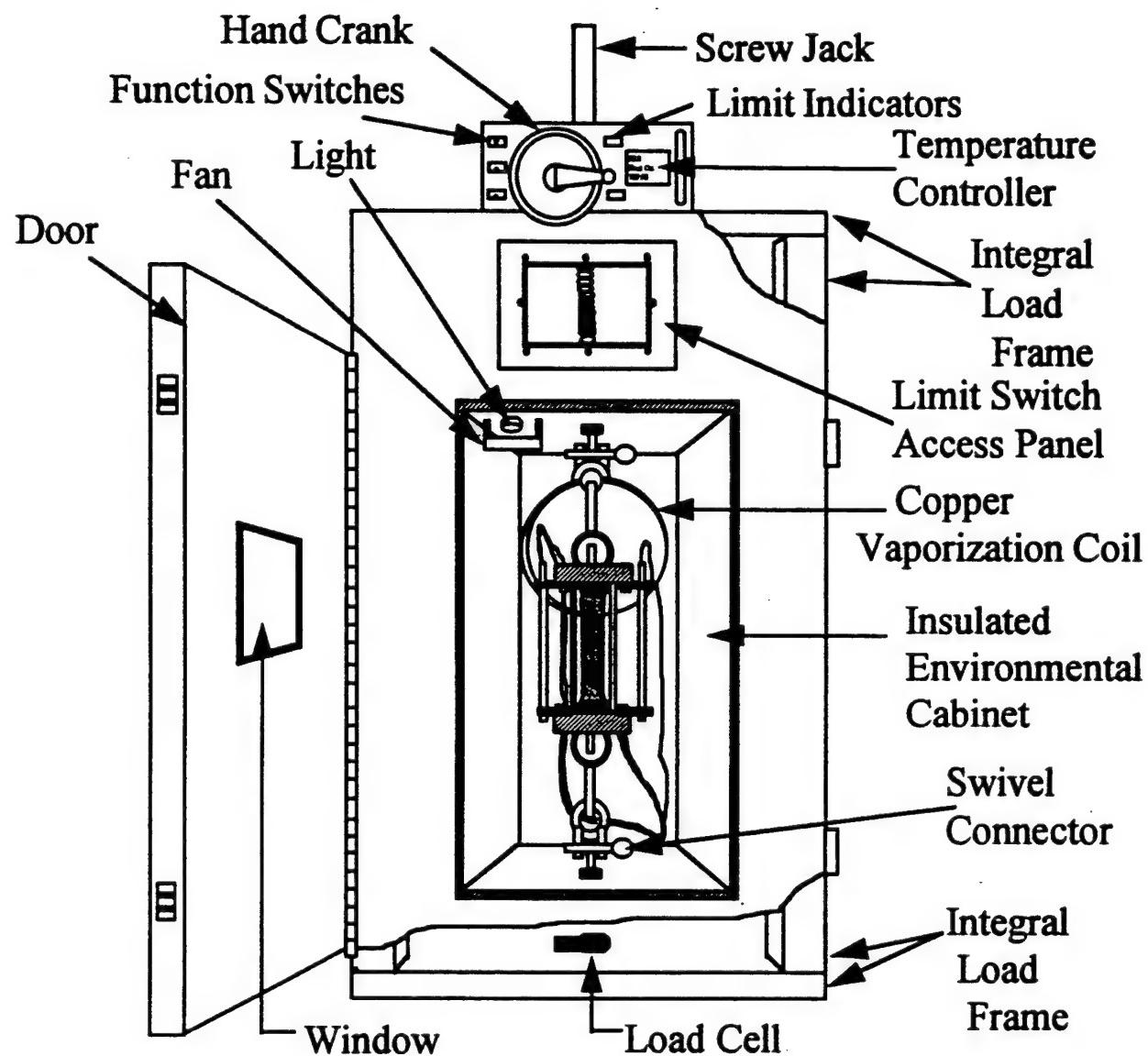
Figure 2.8 - Schematic of Thermal Stress Restrained Specimen Test

Chapter 3

Use of Facility

Educational Aspects

The facility has been used in several ways. As a educational tool, a course entitled "Pavement Materials Characterization" is using the equipment throughout the course. We believe that UTEP is one of the first universities that have incorporated the new equipment in the teaching curriculum.

One student has been working on a project that was initially funded by the UTEP Alliance of Minority Participation (funded by NSF). The project deals with correlating the index parameters used in the state of practice for classifying asphalt cement with the fundamental parameters of asphalt cement measured with the binder testing devices mentioned in Chapter 2. The same student is currently continuing his research under an "Eisenhower Fellowship" awarded to him by the Department of Transportation. The result should be of interest to practitioners.

The UTEP Materials Research Center of Excellence (also funded by NSF) provided support for another student to work on a project that relates the viscosity of the asphalt to the stiffness of the asphalt mixture.

Research Aspects

Two research projects funded by the Texas Department of Transportation and Federal Highway Administration have been extensively using the equipment. These projects, which are competitively awarded, are entitled as follows:

1. "Testing Methods for Reclaimed Asphalt Pavement," September 1993 through August 1995, $137,000, and
2. "Evaluation of Environmental Conditioning System for Predicting Moisture Damage Susceptibility of Hot Mix Asphalt Concrete," September 1994 through August 1996, ($125,000).

Each of these projects are briefly described here. In addition, a copy of two referred papers submitted for publication to the Transportation Research Board are included in appendices.

Testing Methods for Reclaimed Asphalt Pavement[1]

Due to growing environmental and economical concerns, asphalt recycling has become an attractive rehabilitation alternative technique. As the rheological parameters of asphalt change with time due to aging, its constituent properties have to be measured before it is blended with virgin materials. This would ensure high-quality pavement and avoid excessive maintenance cost. The existing methods using Abson recovery, involves many problems, such as utilization of hazardous solvents. The wave propagation techniques can be used to determine the rheological parameters of asphalt without using the hazardous solvents in extraction and recovery process.

A laboratory study was conducted from two different mix designs with three different asphalt contents and the void in total mixes (VTM's). Specimens were aged for 0, 1, 2, 7, and 28 days at 85°C in an oven. All specimens were tested for their elastic moduli and indirect tensile (IDT) Strengths. A V-meter was used to measure the elastic moduli of specimens. The asphalt binder contained in the specimens were extracted and recovered to measure their rheological parameters.

Analyses were conducted to identify mix parameters that best correlate to modulus and IDT strength. Based on the correlation amongst the parameters, models were developed for predicting the penetration and the kinematic viscosity using the elastic modulus or IDT strength.

Using these models along with ASTM specifications for different grades of asphalt, prediction charts were generated to estimate the asphalt grade of RAP materials knowing their moduli or strengths.

Based on the results of this study, the following conclusions were drawn:

1.   The use of wave propagation techniques can be extended to predict the rheological parameters, thereby avoiding Abson recovery.

2.   A linear relationship exists between the modulus and logarithm of penetration (or kinematic viscosity), for a given asphalt content and VTM.

3.   Elastic modulus is affected by both the asphalt content and the VTM in the mix. However, the effects of the VTM are more prominent, on the modulus when compared to the asphalt content of the mix.

4.   The models developed are mix-specific; that is the model should be calibrated for a given mix.

5.   Practically speaking, when the asphalt content is known, models based on elastic modulus can be reliably used to predict the rheological parameters.

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1   The findings of this project has been contained in a thesis by Nori (1995) and a report by Nazarian et al. (1995). Both can be obtained from UTEP.

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6. Prediction charts can be generated to estimate the asphalt grade.

7. Models developed based on the IDT strength can be used as well, to predict the rheological parameters.

Based on this study, the following direction should be pursued:

1. More mix designs including age susceptible mixes have to be studied to evaluate their influence on the models.

2. Necessary validations have to be made to extend the models developed for any type of mix/RAP material.

3. Since most of the aging effects have been observed in the first few days using oven aging method, more attention should be paid to aging periods less than 2 days.

4. The stress-strain curves should be measured during the indirect tensile tests to determine whether other parameters (such as strain energy or strain at failure) may better correlate to the rheological parameters.

Evaluation of Environmental Conditioning System for Predicting Moisture Damage Susceptibility of Hot Mix Asphalt Concrete[2]

Many highway agencies have been experiencing significant damage to pavements due to stripping. The methods commonly used to evaluate the stripping potential of asphalt concrete in the laboratory are good indicators of field performance. To better predict field performance, the Environmental Conditioning System (ECS) was developed at the Oregon State University (OSU) under a contract from the Strategic Highway Research Program (SHRP). The ECS was developed with the objective of simulating field conditions in the laboratory, thus providing a better indication of moisture susceptibility of asphalt concrete mixtures. The initial studies at the OSU exhibited the ECS has the potential for identifying moisture-susceptible mixtures in the laboratory. However, a study conducted by the Colorado DOT indicated the ECS needs to be more critically evaluated and modified.

The basic objectives of this project are: 1) to evaluate the ECS device under conditions encountered in Texas, 2) to compare its versatility with other methodologies already used, 3) to define the strengths and weaknesses of the device, 4) to determine the cost effectiveness of the device, and 5) to outline modified test protocols applicable to the diverse climatic conditions of Texas. The project was divided into two phases. The first phase of the project was to achieve the first three objectives, while the second phase was to implement the information obtained to achieve the last two objectives.

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2   This project is ongoing. The preliminary findings of this project has been contained in a thesis by Vemuri (1996) and a report by Tandon et al. (1996). Both can be obtained from UTEP.

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Kennedy T.W., Multhrop J.S., and Huber G.A. (1993), "Development of SHRP Mixture Specification and Design and Analysis System," Proceedings of Association of Asphalt Paving Technologists, Vol. 62.

Nazarian S., Nori S., Pezo R., and Picornell M. (1995), "Predicting Rheological Parameters of Reclaimed Asphalt Cement with Wave Propagation Techniques," Research Report 1369-1F, Center for Geotechnical and Highway Materials Research, The University of Texas at El Paso, El Paso, TX.

Nori S. (1995), "Rheological Parameters of Reclaimed Asphalt Cement with Wave Propagation Techniques," MS Thesis, The University of Texas at El Paso, El Paso, TX.

Tandon V., Vemuri N., and Nazarian S. (1996), "A Comprehensive Evaluation of Environmental Conditioning System," Research Report 1455-1, Center for Geotechnical and Highway Materials Research, The University of Texas at El Paso, El Paso, TX.

Vemuri N. (1996), "A New Protocol for Conditioning of Specimens Used in Environmental Conditioning System," MS Thesis, The University of Texas at El Paso, El Paso, TX.

APPENDIX A

Rheological Parameters of Reclaimed Asphalt Cement with Wave Propagation Techniques
(A Feasibility Study)

EVALUATION OF ENVIRONMENTAL CONDITIONING SYSTEM

FOR PREDICTING MOISTURE SUSCEPTIBILITY

OF ASPHALT CONCRETE MIXTURES

by

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ABSTRACT

Many highway agencies face the problem of premature failure of asphalt concrete pavements due to moisture damage. Various laboratory tests have been used to predict the moisture susceptibility of asphalt concrete mixtures. Unfortunately, none of the available laboratory tests are able to accurately discriminate between well and poor performing mixes; that is, the laboratory test results do not necessarily correlate well with the field performance. Recent studies performed under the Strategic Highway Research Program (SHRP) indicate that the environmental conditioning system (ECS) is a device that better simulates the field conditions. Based on the initial studies, the ECS seemed to be able to distinguish moisture susceptible mixes. A recent study conducted by the Colorado DOT suggested that the ECS device and testing procedure needed further evaluation before it could be incorporated in the routine use.

A study was undertaken at the University of Texas at El Paso (UTEP) to evaluate the ECS. Based on the results from this study, the ECS needs improvement in the precision and accuracy of the measurements. Specifically, the resilient modulus test setup of the ECS should be improved to obtain more representative results.

INTRODUCTION

Many highway agencies have been experiencing premature failure of pavements. One of the major causes of premature pavement failure is the moisture damage of the asphalt concrete (AC) layer. Moisture damage in the AC pavement occurs due to the loss of adhesion (between asphalt and aggregate) and/or loss of cohesion (i.e. softening of asphalt that weakens the bond between asphalt and aggregate). The stripping of the asphalt from aggregate results in the reduction of strength of the asphalt concrete mixture. The reduction in strength can contribute to the development of various forms of pavement deterioration such as raveling.

A recent survey, conducted by the Transportation Research Board under a National Cooperative Highway Research Program, indicated that 34 states (out of 46 states participating) were to some degree experiencing moisture damage (1). According to the same survey, around 10 to 20 percent of the highways in Texas experience distress due to moisture-related problems.

Conventionally, laboratory tests have been performed to evaluate the moisture susceptibility of the asphalt concrete mixtures. These tests have, to some extent, addressed the problem. However, the results obtained from these tests may not necessarily correlate well with the field observations. To better simulate field conditions, a new testing device called the Environmental Conditioning System (ECS) was developed as part of the research project SHRP A-003A (2). The initial studies showed that the device is promising. However, a recent study by the Colorado Department of Transportation, called for an evaluation of the testing device and for a modification of the

testing protocol before it can be used in every day projects (3). The purpose of this paper is to report on a laboratory evaluation of the ECS device and comparison of its versatility relative to the state-of-practice, namely, the modified Lottman (AASHTO T 283) procedure.

RESEARCH APPROACH

The research was carried out in three steps. In the first two steps, the precision and accuracy of the ECS (AASHTO TP-34) and AASHTO T 283 procedures were determined. While in the third step, a comparison was made between the two test methods. Since a comparison between resilient modulus obtained from ECS test results and indirect tensile strength (ITS) obtained from AASHTO T 283 test results could not be standardized, it was decided to obtain the ITS for the specimens subjected to ECS test procedure. At the conclusion of the last conditioning cycle, specimens were subjected to a load in compliance with the ITS test and the strength at failure was noted. Thus, ECS resilient modulus and ITS were obtained for the same sample without subjecting it to any further conditioning.

Finally, to obtain the ratio of the ITS, unconditioned specimens from each type of the mixtures were subjected to ITS test only and a ratio of the conditioned to the unconditioned was obtained. A ratio of 0.7 (similar to the ratio of ECS resilient modulus) was used to distinguish the moisture susceptible mixtures from the well performing mixtures.

Three different asphalt concrete mixtures were selected (with the assistance of the TxDOT personnel) for the evaluation purposes; two of which have historically performed

well and the one that has performed poorly. The well-performing mixtures were from El Paso, Texas and Colorado Materials Company, while the poor-performing one was from Atlanta, Texas. Although the asphalt used for each three mixtures was from different source, they all graded as AC-20. The aggregate gradation of the mixtures are given in Figure 1 and the mixture specifications and aggregate properties are given in Table 1 and 2, respectively.

To evaluate the precision of the methodologies, tests were performed on five similar specimens of each mixture. The accuracy of the methodologies were evaluated by comparing the outcome of the tests with the historical field performance of the mixtures. To obtain the indirect tensile strength ratios for the specimens conditioned using the ECS, five additional specimens of each mix (15 specimens in total) were prepared. Thus, in all, thirty specimens were prepared for evaluating the ECS, while 120 specimens were prepared for AASHTO T 283 procedure.

TEST PROCEDURES

A brief description of each test procedure is included herein. Test procedures are also summarized in Tables 1 and 2 for convenience. For an in-depth understanding of the ECS procedure, the reader may refer to Al-Joaib (4).

ECS Test Procedure

The specimens used in the ECS procedure were 102± 4 mm in diameter and 102± 4 mm in height. The air void content of all specimens are in the range of 7.5± 0.5 %. The loose

asphalt concrete mixtures are prepared (as per AASHTO TP4-93, Edition 1B) and are short-term aged (in accordance with AASHTO PP2-94, First Edition). The short-term aged mixtures are compacted using a SHRP gyratory compactor (as per AASHTO TP4-93, Edition 1B). The compacted specimens are left at room temperature for 24 hrs. to cool down, and then are encapsulated in a latex membrane with silicone (by injecting the silicone between the membrane and by spreading the silicone around the specimen surface using spatula) and left over night.

The air permeability and dry resilient modulus (MR) of the specimen are determined after it is placed inside the ECS load frame. The air permeability is determined by flowing air through the specimen at a vacuum level of 68 kPa. The resilient modulus is determined by applying a load in the form of a haversine wave with a loading period of 0.1 sec. and a rest period of 0.9 sec. The specimen is then saturated by pulling de-aired distilled water through it at a vacuum level of 68 kPa. In the next step, the water permeability of the specimen is determined.

The saturated specimen was subjected to a "hot cycle" — the specimen's temperature was elevated to 60° C for six hours while it was subjected to the haversine loading. The specimen was cooled down to a temperature of 25° C for at least two to three hours. At the end of the eight to nine hours, the conditioned MR and the water permeability were determined. The process was repeated for two more cycles i.e. six hours of loading and heating at 60° C. If the ratio of the conditioned MR to the unconditioned MR was below 0.7, the mixture was considered as moisture susceptible and vice versa.

The conditioned specimens along with the unconditioned specimens were then tested for their indirect tensile strengths. Both specimens were subjected to indirect tensile loads at a rate of 50 mm/min. The indirect tensile strengths and the ratio of the unconditioned strength to that of the conditioned strength are reported for each of the mix. The broken conditioned specimen was then visually inspected to evaluate the percentage of stripping. But, due to a difficulty in interpreting the results, the visual evaluation results have not been reported. Similarly, due to the lack of the guidelines on the use of the measured water and air permeabilities these have not been reported.

Although, the ECS procedure recommends a freezing cycle for some regions, this cycle was omitted in this study because it was not deemed necessary for the climate of Southwestern U.S.

AASHTO T 283 Test Procedure

Eight similar asphalt concrete specimens of a mixture are prepared. The moisture susceptibility of a mixture is evaluated on the basis of the average properties of four conditioned and four unconditioned specimens.

Each specimen is prepared by heating the asphalt and aggregates and mixing them. The loose mix is then subjected to a minimum of 2.5 hours of cooling at room temperature followed by a short-term aging at 60°C for a period of 15 hours. The short-term aged mixture is then heated at 135 °C for a period of 2 hours before being shaped into specimens with an air void content of 7.0± 0.5 % using a SHRP Gyratory compactor. The compacted specimen (102± 4 mm in diameter by 63.5± 1 mm in height) is cooled at room

temperature for a period of 24 hours.

The eight specimens are then divided into two groups of four. One group is left in a desiccator until tested for their indirect tensile strength. Meanwhile, the second group is subjected to vacuum saturation at 68 kPa for 5 to 10 minutes so that 50 to 80 % of the specimen's air voids are filled with water . The saturation period depends on the air void content and permeability of the specimen. The saturated specimens are then kept in plastic bags (two per bag) along with 10 ml of distilled water. The bags are then kept in a freezer, maintained at a temperature of -18°C, for a span of 15 hours. The specimens are then transferred to a water bath maintained at 60°C for 24 hours, followed by a water bath at a temperature of 25°F for a period of 4 hours.

The specimens, including the four specimens kept in the desiccator, are tested for their indirect tensile strengths at a loading rate of 50 mm/min. The ratio of the average tensile strengths of the conditioned specimens to that of the unconditioned specimens is then determined. If the ratio is below 0.7, the mixture will be considered as susceptible to moisture damage.

RESULTS AND DISCUSSIONS

The results from the two testing procedures performed on the three different mixes are summarized in Tables 5 through 9 and Figures 2 through 6. In Tables 5 through 7 the results obtained from the ECS testing of the three mixtures are summarized. Table 8 shows the results from AASHTO T 283 procedure and Table 9 summarizes the statistical analysis of the two methods. Figures 2 through 4 show changes in the ECS resilient

modulus values after each conditioning cycle for the three mixtures. In Figures 5 and 6, the indirect tensile strength ratios obtained from the two tests are compared.

ECS Test Results

As indicated before, the moisture susceptibility of a mix is determined based on the ratio of the unconditioned and conditioned resilient moduli. The ratio is called the resilient modulus ratio. The MR ratio values of the El Paso mix varied from 0.27 to 0.80, indicating a poor precision (see Table 5). Specimen numbers 1, 2, 4, and 5 can be classified as moisture susceptible, while specimen number 3 indicates that the mix is acceptable. Historically, the El Paso mix has not exhibited any moisture susceptibility.

The detailed results of the ECS tests are shown in Figure 2. In terms of MR ratios, only specimens 1 and 2 nearly follow the same pattern from one cycle to another, while the other specimens exhibit different behaviors.

For the Colorado mix, the MR ratios varied from 0.62 to 0.82 (Table 6). The results from specimens 1 and 3 indicate that the mix is moisture susceptible. On the other hand, according to the results from specimens 2, 4, and 5 the mix should be suitable. The Colorado mix is historically considered as a satisfactory mixture. Figure 3 depicts the MR ratios after each cycle for each specimen. Contrary to the El Paso mix, all specimens (except specimen 5) yielded similar MR ratios after the second cycle.

The MR ratios for the Atlanta mix, a moisture-susceptible mix, varied from 0.64 to 1.42 indicating a lack of repeatability. As per Table 7 only the results from specimen 5 indicate any moisture susceptibility. The other specimens passed the criteria of MR ratio

of 0.7. The Atlanta mix is considered moisture susceptible, and is usually placed with an anti-stripping agent added to the mix. Figure 4 shows that the MR ratios after each cycle is different for each specimen of the Atlanta mix, indicating a large variability in the results.

AASHTO T 283 Test Results

The results obtained from this test procedure are summarized in Table 8. The average indirect tensile strength ratios for the El Paso mix varied from 0.59 to 0.98. All specimens, except number 4, yield strength ratios in excess of 0.7, indicating that the mixture is not moisture susceptible. This conclusion is in concurrence with the historical field performance of the El Paso mix.

The indirect tensile strength ratios of all specimens prepared from the Colorado mix are about 0.9 indicating that the mixture should not be moisture susceptible. Based on historical performance, the Colorado mix is not prone to moisture damage. The results from the five tests are quite repeatable and do not vary by more than 0.1.

Based on the ITS ratios obtained from the specimens of the Atlanta mix, it should perform well. The average tensile strength ratios of the five tests varied from 0.96 to 1.13. Unfortunately, this conclusion is not supported by the historical performance of this site. Once again, the results are quite repeatable.

Comparison of Two Methodologies

The test results obtained from the two test procedures indicate that the AASHTO T 283 test method yields more precise (repeatable) results as compared to the ECS test procedure. However, neither of the two tests is accurate enough to consistently discriminate between a well-performing and a poor-performing mix.

The averages, standard deviations and coefficients of variation corresponding to each mixture for three parameters are included in Table 9. The three parameters are: 1) the resilient modulus ratios from the ECS, 2) the ITS ratios from tests performed on the specimens that were conditioned in the ECS, and 3) the ITS ratios from the AASHTO T 283 tests.

The repeatability of the test methods can be determined by comparing the coefficients of variation (CV) reported for the three parameters. For the ECS MR ratios, the CV seems to be dependent on the mix. For two of the mixes, the CV's are about 35 percent, whereas for the third one it is about 10 percent. Such variation cannot be attributed to the operator since all tests were performed by one person. The variation cannot be due to the variability in preparing the specimens, because the coefficients of variation associated with the ITS tests performed on the identical specimens are about 10 percent.

In our opinion, the source of the deficiency is the resilient modulus set-up. As compared with the rigidity of the specimen, the compliance of the test frame may not be adequate. This may be remedied by redesigning the loading system. The other source of problem is the method of mounting of the LVDT's. At this time, the LVDT's are being

replaced with non-contact probes to minimize this problem.

The repeatability of the AASHTO T 283 seems to be satisfactory , since the CV variation are typically about 6 to 7 percent. For the El Paso mix, the CV is about 17 percent because of one obvious outlier (see Table 8).

The degree of moisture conditioning of the ECS and AASHTO T 283 can be compared by inspecting the averages of the ITS ratios from the two tests. For the three mixtures tested, it seems that the two systems more or less provide the same level of conditioning. The average ITS ratios for the El Paso mix are 0.68 and 0.82 for the ECS and AASHTO T 283, respectively. Therefore, the ECS is providing slightly harsher conditioning for El Paso mix. For the Colorado mix, the ITS ratios are about 0.9 for both test methods, which can be interpreted as similar levels of conditioning. Finally, for the Atlanta mix, it seems that the effects of ECS conditioning is nil, since the ITS ratios are close or greater than unity. This implies that the ECS conditioning was different for different mixes and actually did not predict the correct performance of the mixes.

Based on our experience, the conditioning of the ECS can be modified by heating the water circulating in the specimen during the hot cycles from 25 °C to about 60 °C.

CONCLUSIONS AND RECOMMENDATIONS

Based on the above discussion, it can be concluded that both test procedures need modification in order to consistently identify moisture susceptible mixtures. In the existing form, the AASHTO T 283 test procedure seems to be more precise as compared to ECS test procedure. However, based on the indirect tensile strength ratios measured on the specimens conditioned with the ECS, the variability may be due to the MR measurement setup.

On the basis of this research, the following modifications are suggested in the ECS testing procedure for obtaining more accurate and precise results:

- The resilient modulus measurement system should be modified to yield more precise results.

- The indirect tensile strength ratio test should be included as a part of the ECS test procedure.

Work on these lines is on going at the University of Texas at El Paso.

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TABLE 1.   Mix Specifications

Mix Type	Asphalt Type	Aggregate Type	Rice Specific Gravity
El Paso	AC-20	Limestone	2.471
Colorado	AC-20	Limestone	2.430
Atlanta	AC-20	Siliceous gravel	2.425

TABLE 2.   Aggregate Properties

Properties	El Paso	Colorado	Atlanta
SE*	45	78	59
WA**	12	0.7	-
BSG***	2.59	2.65	2.63

*   Sand Equivalent
**   Water Absorption
***   Bulk Specific Gravity

Table 3.   Summary of AASHTO T 283 Procedure

Specimens	8 samples divided into 2 sets of 4 samples each size: 102± 4 mm. diameter by 63.5 ±1 mm. height	
Mixing	Mix asphalt and aggregate for eight specimens; cool the loose mix for minimum 2.5 hours @ room temperature; cured @ 60°C for 15 hours.	
Compaction	Mixture specimens heated @ 121°C for 2 hours; specimens were compacted to 93± 1% of theoretical maximum specific gravity using SHRP gyratory compactor. Specimens cooled to room temperature for 24 hours	
Air Voids (%)	6.5 to 7.5%	
Procedure	Sort specimens into two subsets of four specimens	
	Group I:	(unconditioned) store @ room temperature in a dessicator until ready to test for Indirect Tensile Strength Test
	Group II:	(conditioned) Partial vaccum (508 mm. Hg) for 5 - 10 min until the degree of saturation is 50-80% - Freeze @ -17.78°C for 16 hours followed by soaking in a 60°C bath for 24 hours - Place in water bath @ 25°C for 2 hours prior to testing
DamageAnalysis	Diametral Indirect Tensile Strength Test (ASTM D4123-82)	

Table 4. **Summary of ECS Test Procedure**

Step	Description
1	Prepare 102±4 by 102±4 mm. specimens using SHRP gyratory compactor.
2	Determine the geometric and volumetric properties of the specimen.
3	Encapsulate specimen in silicon sealant and latex rubber membrane, allow to cure overnight (16 hours).
4	Place the specimen in the ECS load frame, between two perforated teflon disks, determine air permeability.
5	Determine unconditioned (dry) ECS resilient modulus by applying a static load of 130 ± 25N and a maximum load of 2200± 25N. The loads should be adjusted so as to obtain an average strain between 50 and 100 strain.
6	Vacuum condition specimen (subject to vacuum of 68 KPa for 10 minutes).
7	Wet specimen by pulling distilled water through specimen for 30 minutes using a vacuum of 68 kPa.
8	Determine the unconditioned water permeability.
9	Heat the specimen to 60°C for 6 hours, under repeated loading of 900± 25N of maximum load and 90± 5N of static load. This is a hot cycle.
10	Cool the specimen to 25°C for at least 2 hours(usually it takes more than 3 hours for the specimen to cool to 25°C). Measure the ECS resilient modulus and water permeability.
11	Repeat steps 9 and 10 for 2 more hot cycles.
12	Split the specimen and perform a visual evaluation of stripping.
13	Plot the ECS resilient modulus and water permeability ratios.

TABLE 5.   Summary of ECS Test Results for El Paso Mix

NO.	VTM (%)	Cycle No.	Average Resilient Modulus (GPa)	Resilient Modulus Ratio	ITS[**] (MPa)	ITSR[+]
1	8.0	0*	0.94	1.00	0.54	
		1	0.65	0.70	N/A	
		2	0.48	0.51	N/A	
		3	0.55	0.59	0.37	0.69
2	7.5	0	0.99	1.00	0.57	
		1	0.55	0.56	N/A	
		2	0.48	0.50	N/A	
		3	0.53	0.54	0.32	0.56
3	7.7	0	0.77	1.00	0.53	
		1	0.66	0.86	N/A	
		2	0.68	0.88	N/A	
		3	0.62	0.80	0.42	0.81
4	7.2	0	1.02	1.00	0.49	
		1	0.50	0.49	N/A	
		2	0.48	0.47	N/A	
		3	0.28	0.27	0.32	0.65
5	8.0	0	0.80	1.00	0.53	
		1	0.40	0.50	N/A	
		2	0.48	0.60	N/A	
		3	0.40	0.50	0.36	0.67

*   Cycle 0 represents tests before conditioning
**   ITS denotes indirect tensile strength
+   ITSR denotes indirect tensile strength ratio

TABLE 6.   Summary of ECS Test Results for Colorado Mix

NO.	VTM (%)	Cycle No.	Average Resilient Modulus (GPa)	Resilient Modulus Ratio	ITS** (MPa)	ITSR+
1	7.7	0*	1.40	1.00	0.56	
		1	0.94	0.68	N/A	
		2	1.04	0.75	N/A	
		3	0.86	0.62	0.54	0.96
2	7.3	0	1.47	1.00	0.66	
		1	0.91	0.62	N/A	
		2	1.08	0.74	N/A	
		3	1.03	0.71	0.59	0.90
3	7.9	0	1.49	1.00	0.64	
		1	0.88	0.59	N/A	
		2	1.04	0.70	N/A	
		3	0.99	0.66	0.54	0.86
4	7.5	0	1.74	1.00	0.67	
		1	1.52	0.87	N/A	
		2	1.26	0.73	N/A	
		3	1.23	0.71	0.56	0.83
5	7.9	0	1.01	1.00	0.64	
		1	0.98	0.97	N/A	
		2	1.04	1.03	N/A	
		3	0.82	0.82	0.66	1.03

*   Cycle 0 represents tests before conditioning
** ITS denotes indirect tensile strength
+   ITSR denotes indirect tensile strength ratio

TABLE 7.   Summary of ECS Test Results for Atlanta Mix

NO.	VTM (%)	Cycle No.	Average Resilient Modulus (GPa)	Resilient Modulus Ratio	ITS** (MPa)	ITSR+
1	7.4	0*	1.55	1.00	0.71	
		1	0.44	0.28	N/A	
		2	0.93	0.60	N/A	
		3	1.13	**0.73**	0.81	**1.14**
2	7.5	0	1.93	1.00	0.69	
		1	2.83	1.47	N/A	
		2	2.50	1.30	N/A	
		3	2.73	**1.42**	0.76	**1.11**
3	7.8	0	2.12	1.00	0.67	
		1	2.43	1.15	N/A	
		2	3.03	1.43	N/A	
		3	2.50	**1.18**	0.88	**1.32**
4	7.6	0	3.33	1.00	0.64	
		1	2.67	0.80	N/A	
		2	2.96	0.89	N/A	
		3	2.73	**0.82**	0.75	**1.16**
5	7.3	0	4.18	1.00	0.69	
		1	3.65	0.87	N/A	
		2	3.42	0.82	N/A	
		3	2.67	**0.84**	0.74	**1.07**

*   Cycle 0 represents tests before conditioning
**   ITS denotes indirect tensile strength
+   ITSR denotes indirect tensile strength ratio

Table 8. Summary of Results Obtained for AASHTO T 283 Test

a) El Paso Mix

No.	Average Indirect Tensile Strength (kPa)		Indirect Tensile Strength Ratio
	Unconditioned	Conditioned	
1	584	571	0.98
2	348	277	0.80
3	542	467	0.86
4	598	354	0.59
5	587	515	0.88

b) Colorado Mix

No.	Average Indirect Tensile Strength (kPa)		Indirect Tensile Strength Ratio
	Unconditioned	Conditioned	
1	609	626	1.03
2	685	620	0.91
3	713	632	0.89
4	688	625	0.91
5	697	634	0.91

c) Atlanta Mix

No.	Average Indirect Tensile Strength (kPa)		Indirect Tensile Strength Ratio
	Unconditioned	Conditioned	
1	695	785	1.13
2	749	748	1.00
3	1509	1509	1.00
4	727	701	0.96
5	808	806	0.99

Table 9. Statistical Analyses of ECS and AASHTO T 283 Test Results

	Resilient Modulus Ratio (MR)			ECS Indirect Tensile Strength Ratio			AASHTO T 283 Indirect Tensile Strength Ratio		
Mix Type	Average	Standard Deviation	Coeff. of Variation (%)	Average	Standard Deviation	Coeff. of Variation (%)	Average	Standard Deviation	Coeff. of Variation (%)
El Paso	0.54	0.19	35.2	0.68	0.09	13.2	0.82	0.14	17.2
Colorado	0.70	0.07	10.0	0.92	0.08	8.7	0.93	0.06	6.5
Atlanta	0.96	0.33	34.4	1.16	0.10	8.6	1.02	0.07	6.9
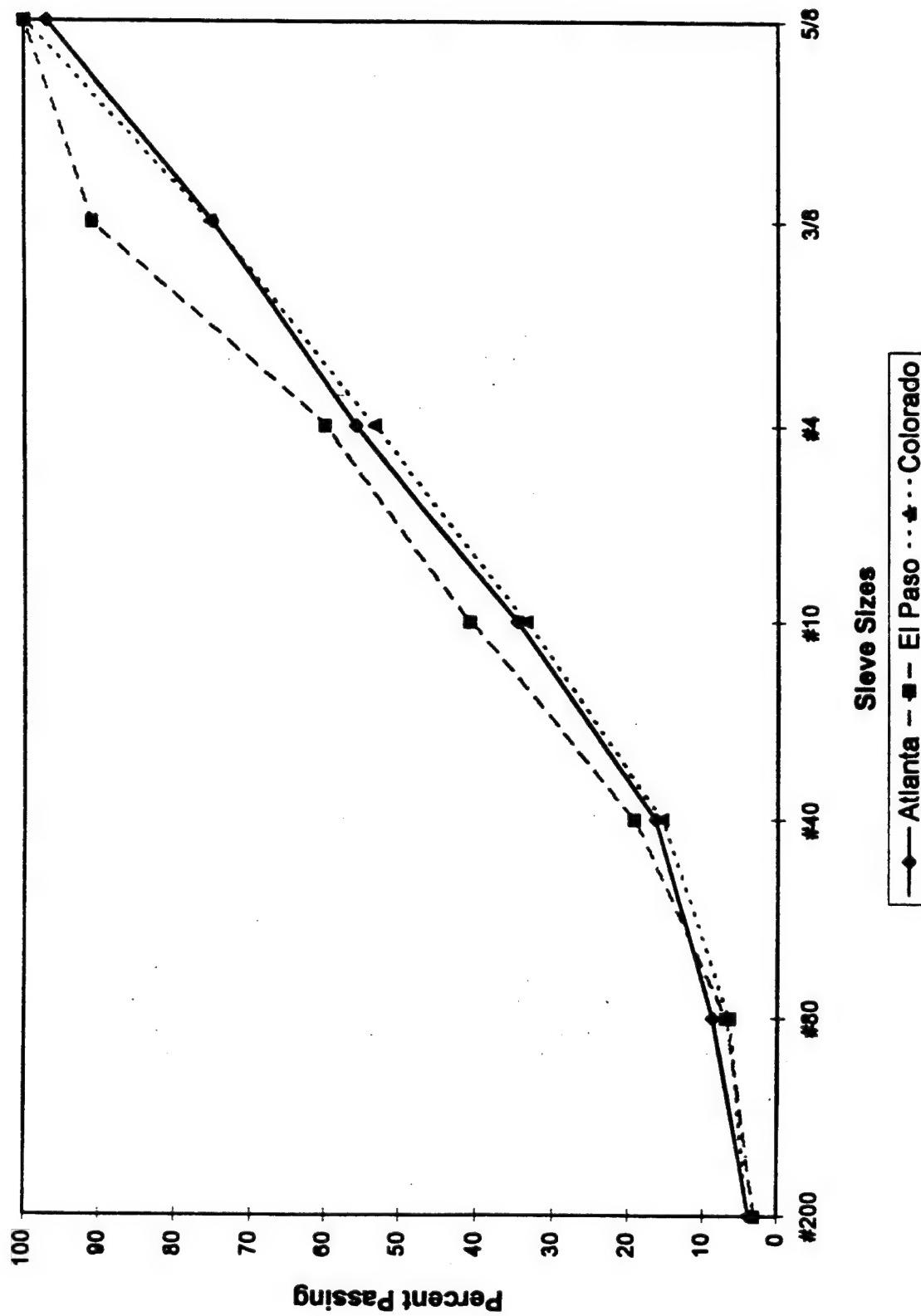
Figure 1. Gradation chart for the Aggregates of the Mixes
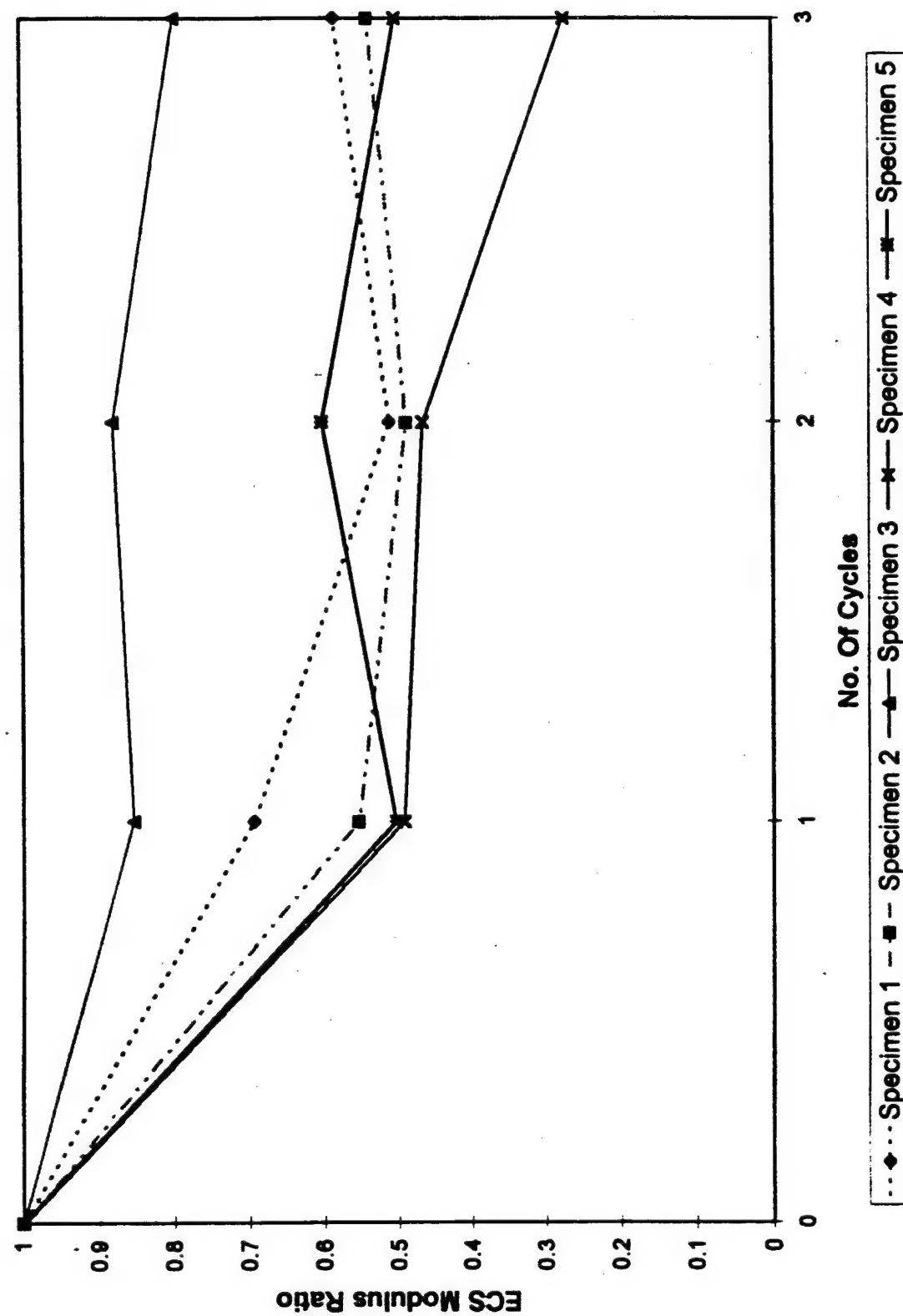
Figure 2. Resilient Modulus Ratios for El Paso Mix
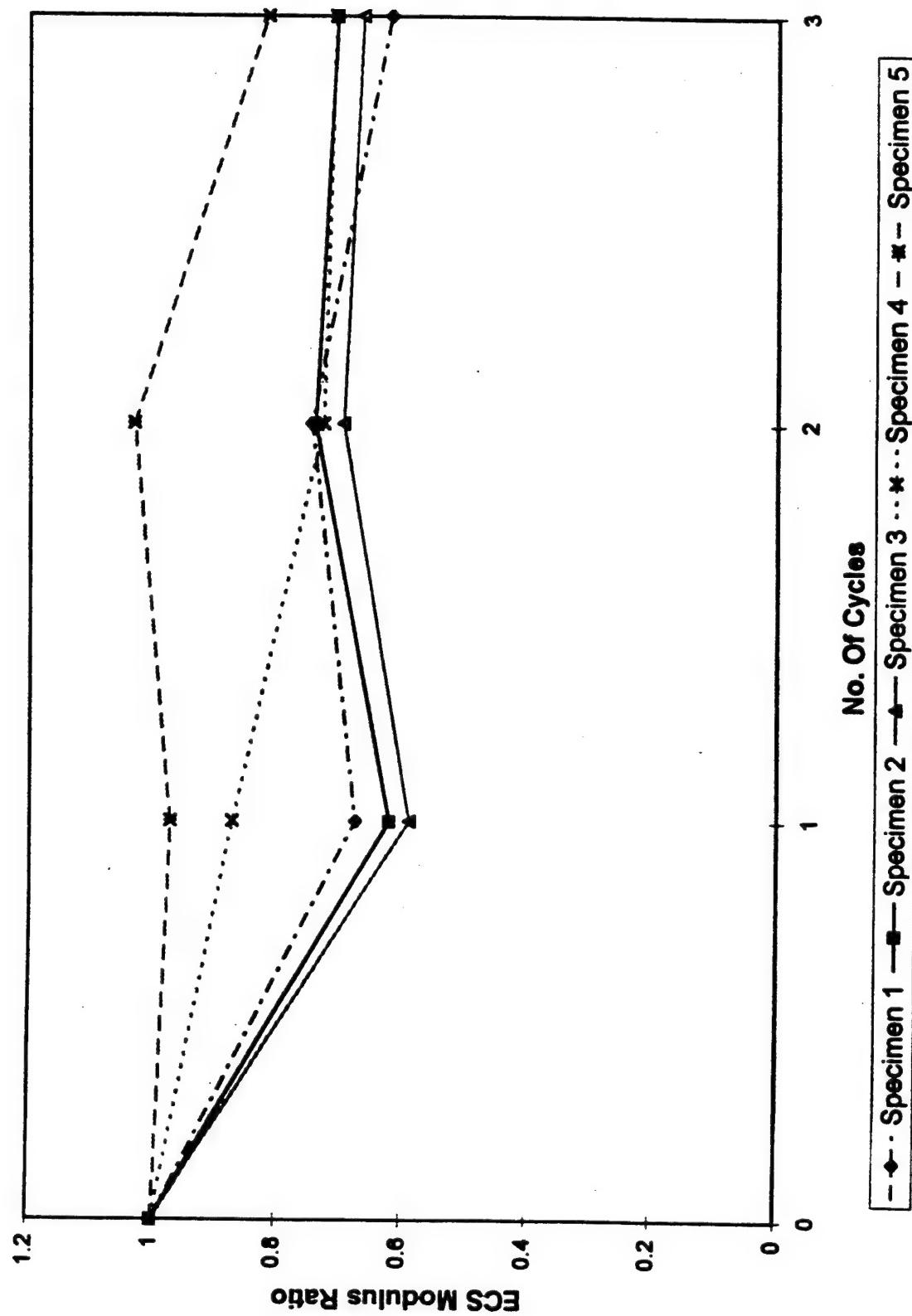
Figure 3. Resilient Modulus Ratios for Colorado Mix

--◆-- Specimen 1 —■— Specimen 2 —▲— Specimen 3 ··✻·· Specimen 4 — ✻ — Specimen 5
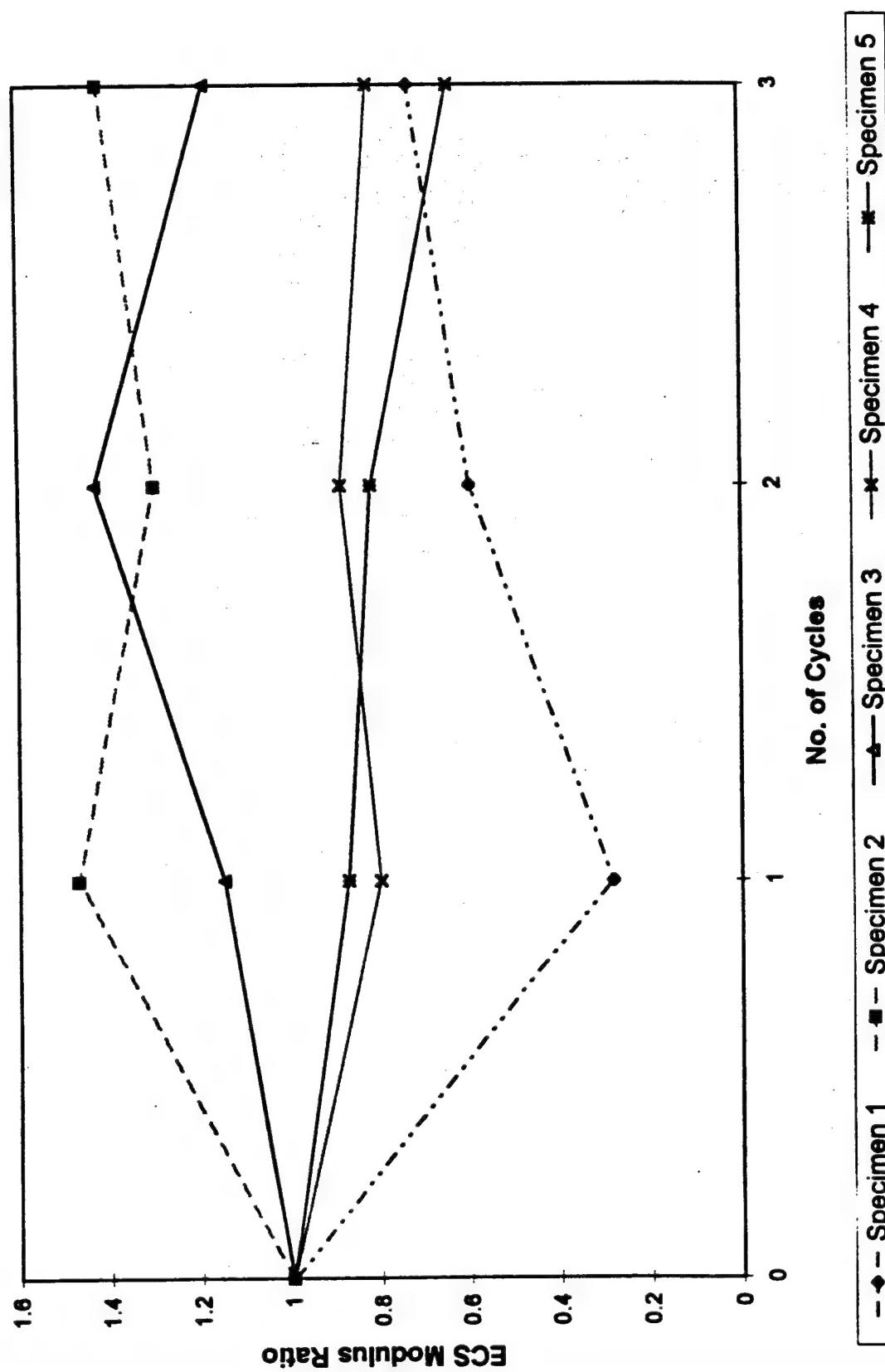
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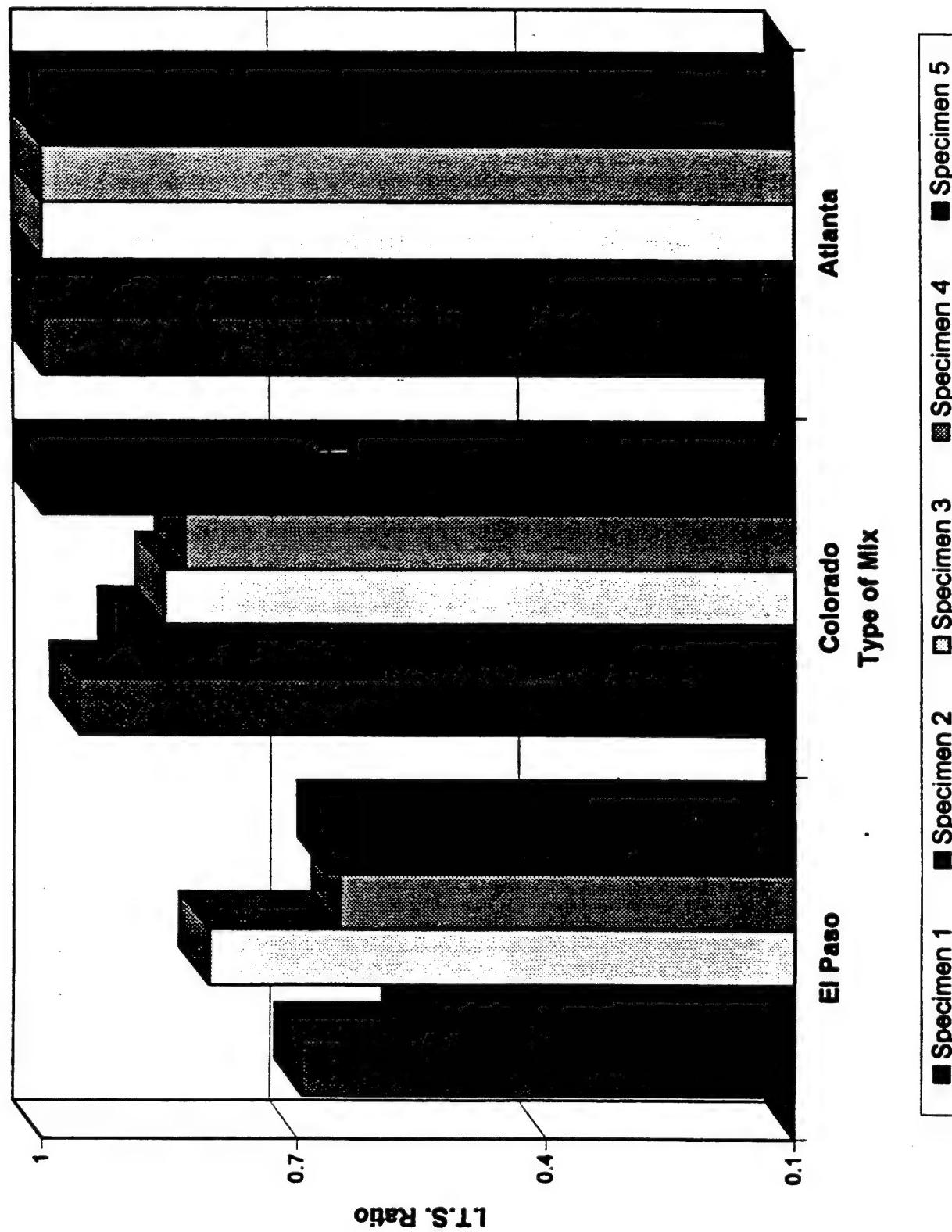
Figure 5. Indirect Tensile Strength Test (I.T.S) Ratios for ECS Conditioned Specimens
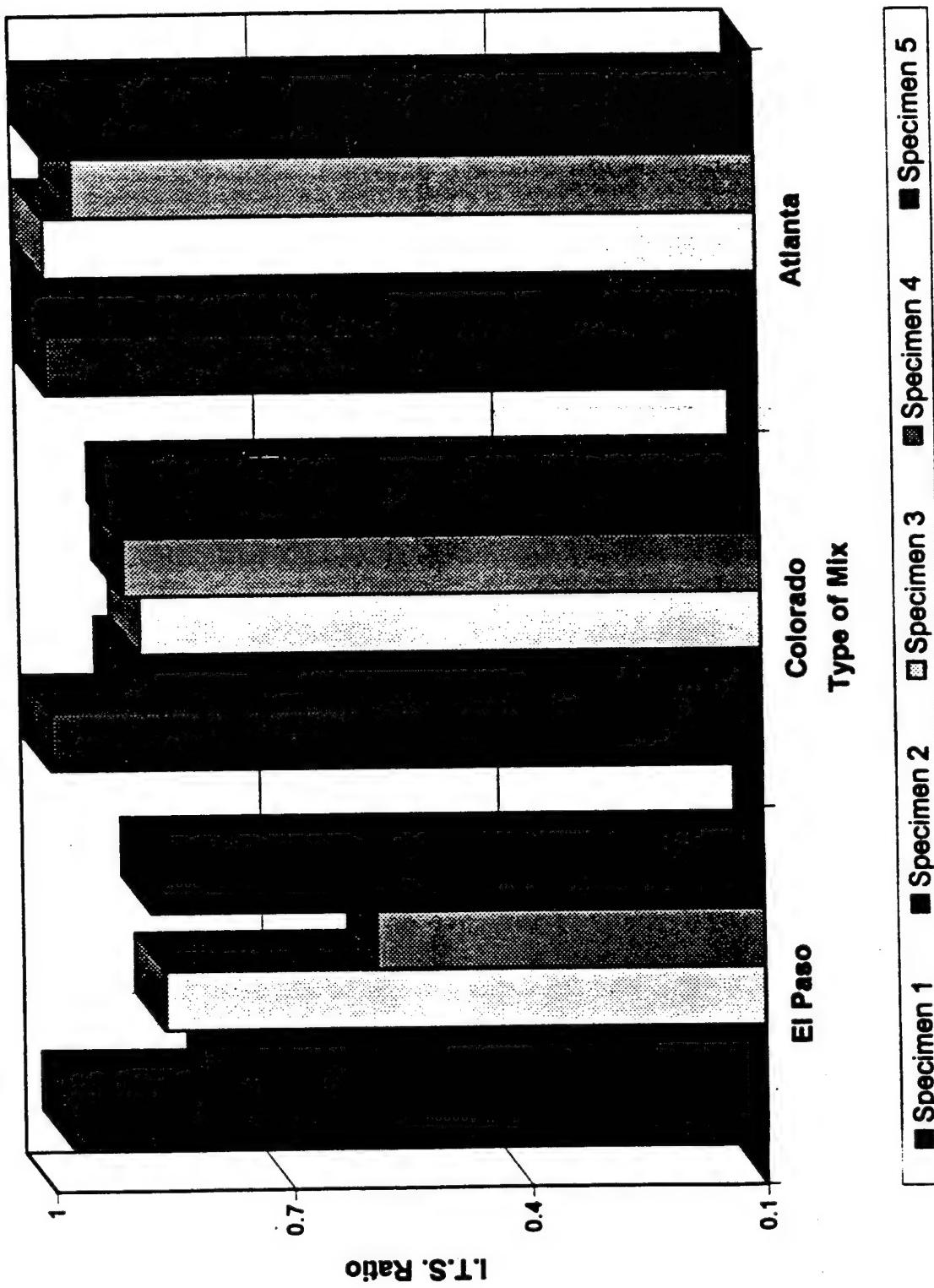
Figure 6. Indirect Tensile Strength(I.T.S) Ratios for AASHTO T 283 Conditioned Specimens

APPENDIX B

Evaluation of Environmental Conditioning System

Rheological Parameters of Asphalt Cement from Wave Propagation Techniques (A Feasibility Study)

by

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A paper for possible inclusion in
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Abstract

To ensure a high-quality pavement and to avoid excessive maintenance costs, reclaimed asphalt pavement (RAP) materials should be properly characterized before reuse. However, the determination of the rheological parameters of RAP materials from extracted asphalt is time consuming and requires the use of hazardous solvents.

Several researchers have proposed the existence of relationships between the viscosity or penetration of asphalt cement and the mechanical properties of a mix. THE Indirect tensile test or diameteral resilient modulus test is used to assess the mechanical properties. In this paper, the use of wave propagation techniques is proposed as an alternative method to estimate the modulus of a mix, because they are easy to use, rapid, repeatable, and nondestructive. In addition, the same test that can be performed in the laboratory can be performed in the field.

The feasibility of using wave propagation techniques to estimate the rheological parameters of asphalt is discussed herein. A complete factorial experiment was carried out. Numerous specimens, prepared from two mixtures having different asphalt contents and voids-in-the-total-mixes (VTM's), were oven-aged for different periods of time. The elastic modulus of each specimen was determined, and its asphalt cement was recovered to evaluate its rheological properties. Once the effects of the important parameters were established, regression models and prediction charts were developed to estimate the asphalt grade of the binder.

In general, it was found that wave propagation techniques can be used to estimate the rheological parameters of asphalt cement. However, the model chosen for use has to be calibrated for each mix. Research aimed at defining the calibration process is now under way.

Rheological Parameters of Asphalt Cement from Wave Propagation Techniques
(A Feasibility Study)

S. Nazarian, R. Pezo, and S. Nori

Introduction

In following the hot-mix method of recycling, 20 to 70 percent of the reclaimed asphalt pavement (RAP) materials used are added to virgin materials. To ensure the quality of pavement and to avoid excessive maintenance costs, RAP materials should be properly characterized before being blended with virgin asphalt and aggregate. Since asphalt cement hardens with time, the rheological properties of aged asphalt cement have to be evaluated. This is typically done by extracting and recovering the asphalt cement from the RAP material. The major problem with this process, besides being labor-intensive, is its utilization of hazardous solvents, the disposal of which is expensive and difficult. A simple and economical methodology that uses a nondestructive method is believed to be useful to assess the degree of aging of RAP material.

In this study, the feasibility of developing prediction models that utilize wave propagation techniques to determine the rheological properties of hardened asphalt was evaluated. The test program consisted of preparing and artificially aging asphaltic concrete specimens, determining their elastic moduli, and assessing such rheological properties as kinematic viscosity and penetration of the recovered binder. This paper describes the test procedure that was followed to determine the properties of a mix and a binder. The process involved in developing the models is also described.

Background

The hardening or stiffening of asphalt binder with time has been referred to as age hardening, embrittlement, and, more simply, "aging" (Bell, 1990). The aging of binder, which results in an increase in the elastic modulus of a mix, depends on various factors, including asphalt characteristics, the asphalt film thickness around the aggregate surface, air voids in the asphaltic concrete mixture (Roberts et al., 1991), and the adsorptive nature of the aggregate (Verhasselt and Choquet, 1992). The type of aggregate used also affects the aging of a mix (Sosnovake et al., 1992). According to Harvey and Monismith (1992), variations in fine content, even those within typical gradation specifications, can affect the aging of a mix.

The extent of aging of asphalt binder can be determined from changes in its rheological properties, such as viscosity and penetration. Penetration at 25°C (77°F) and viscosity at either 135°C (275°F) or 60°C (140°F) are usually specified (Page et al., 1984).

The Resilient Modulus (M_R) test has been used by many researchers to measure the modulus of HMA. For example, Bell et al. (1994) observed an increase in the resilient modulus with the extent of aging of a mix.

Tia et al. (1988) and Von Quintus et al. (1991) used the indirect tensile strength (IDT Strength) test to evaluate the extent of aging. Norman et al. (1990) observed a strong relationship between the penetration of recovered asphalt at 25°C (77°F) and the indirect tensile strength of a mix. They also found that the types of asphalt and aggregate used significantly affect this relationship.

Nazarian et al. (1992) utilized a simple laboratory and two nondestructive field testing techniques to determine variations in modulus with aging. In their approach, the high frequency surface-wave and body-wave methods were utilized to determine shear and compression wave

velocities. From these two parameters, the elastic modulus and Poisson's ratio of the material were calculated. Based on laboratory and field case studies, the researchers concluded that wave propagation techniques, when used properly, can yield valuable information about the aging properties of asphaltic concrete layers.

The above techniques were successfully used by Li and Nazarian (1995) to determine the degree of aging of asphaltic concrete. They quantified the variation in elastic modulus with temperature, aging period, voids-in-total-mix (VTM), and asphalt content.

Baker et al. (1995) have developed a relatively inexpensive, hand-held device that can perform the necessary wave propagation tests on an asphalt layer *in situ* in less than 30 seconds. The device will hopefully aid researchers in their future performance of extensive studies.

Test Procedure

The research activities that were conducted are outlined in Figure 1. Specimens were prepared as per mix design. A replicate of each specimen was made, and the pair of specimens was age-conditioned. Each pair fell into one of two categories: "virgin" or "aged." The "virgin" specimens were tested for their elastic moduli without any age conditioning. The pair of "aged" specimens was first tested at 25°C to determine each specimen's elastic modulus and then placed in an oven set at 85°C, for aging. After a pair of specimens was aged for a predetermined period of time, the specimens' elastic moduli at 25°C were again measured to determine the rate of change in the stiffness. The asphalt binder from each specimen was then extracted and recovered to determine its penetration and kinematic viscosity. To recover enough asphalt to conduct penetration and viscosity tests, the two replicate specimens were mixed

together for extraction and recovery. Finally, as discussed later, the data were analyzed to obtain a correlation.

A complete factorial experiment, considering the various factors that affect the aging of AC mixes, was devised. Two different mixtures were considered in the experimental program: one obtained from an HMA plant in El Paso, Texas and another obtained in Austin, Texas.

The optimum asphalt content for both mixes was about 5 percent. To study the effects of asphalt content, asphalt contents of 4, 5, and 6 percent were selected for each mix. Similarly, specimens were prepared using different compaction efforts to achieve three levels of voids-in-the-total-mix (VTM); i.e., 3, 5, and 7 percent (target VTM's). The specimens were aged for periods of one, two, seven, or twenty-eight days.

The aggregates of the Austin mix contained rock (limestone) and sand obtained from the Hunter Pit of Colorado Materials Quarry. The asphalt was AC-20, obtained from the Texas Fuel and Asphalt Co., Corpus Christi, Texas. The aggregates of the El Paso mix contained rock (dolomite) and sand obtained from McKelligan Canyon and the American Basin of El Paso, respectively. The asphalt was again AC-20, obtained from Chevron USA, Inc.

The laboratory setup used in this study is shown in Figure 2. The elastic modulus of a specimen was measured using an ultrasonic testing device (commercially marketed as a V-meter) containing a pulse generator and a timing circuit, coupled with piezoelectric transmitting and receiving transducers. A pulse having a dominant frequency of 54 KHz was used to generate the necessary waves. The timing circuit digitally displayed the time needed for a wave to travel through a specimen. To ensure full contact between the transducers and a specimen, special removable epoxy couplant caps were used on both transducers. To secure the specimen in between the transducers, a loading plate was placed on top of it, and a spring-supporting system

was placed underneath the transmitting transducer. Each specimen was placed in a temperature-controlled chamber maintained at $25 \pm 0.1°C$ for about fifteen minutes to ensure a constant temperature.

Compression wave (P-wave) velocity, V_p, was calculated by dividing the thickness of the specimen by the corresponding travel time (measured with the V-meter). The elastic modulus, E, was then calculated using

$$E = \rho \ V_p^2,$$ (1)

where ρ is the bulk density of the specimen.

For practical use, Equation 1 can be rewritten as

$$E = \frac{WH}{(\pi R^2 g t^2)},$$ (2)

where

W = Weight of specimen,

R = Radius of specimen,

H = Height of specimen,

g = acceleration of gravity, and

t = travel time.

The extraction of asphalt from the asphalt-aggregate mixture was carried out as per ASTM D2172, using trichloroethylene (TCE) as a solvent. Following ASTM D1856, the asphalt from the solution containing asphalt and solvent was recovered. The penetration (ASTM D5) and the kinematic viscosity (ASTM D2170) of the recovered asphalt were then measured.

Presentation and Discussion of Results

A typical variation in elastic modulus with aging period is illustrated in Figure 3. The modulus of the mixture increases more or less linearly with the logarithm of aging period. This is to be expected, given that a mix hardens during the aging process, resulting in an increase in modulus.

For a given aging period, the moduli of specimens having a 3-percent VTM are greater than those of specimens having a 5-percent VTM, which, in turn, are larger than the moduli of specimens having a 7-percent VTM. An increase in the VTM results in a decrease in the bulk density and, hence, a decrease in the modulus of the modulus. The Y-intercept and slope of each fitted line correspond to the value of the modulus after one day of aging and the rate of increase in the modulus with aging period, respectively. The rate of increase in modulus is higher for specimens having a 5-percent VTM than for those having a 3-percent VTM. The rate of increase in modulus with time is similar for specimens having 5- and 7-percent VTM's.

In general, the modulus of any mix increases with increases in the aging period and with decreases in the VTM. A linear relationship exists between the modulus and the logarithm of aging period. The slope of this relationship varies with the VTM and the AC content.

The relationship between the elastic modulus and the logarithm of penetration, as shown in Figure 4a, is inversely linear. Similarly, a linear relationship between the elastic modulus and the kinematic viscosity is shown in Figure 4b. The similarity in the results from two similar specimens shows that the test procedures are repeatable.

Development of Prediction Models

To assist in the development of prediction models, statistical analyses were performed on the experimental data obtained in this study. The ability of the developed models to predict the rheological properties of asphalt cement was analyzed. Additionally, analyses of normality were performed to determine the applicability of results.

The models that best related the modulus to the penetration and viscosity of the binder, asphalt content, and VTM were found to be

$$E = a_1 + a_2 \, LogP + a_3 \, AC + a_4 \, VTM, \tag{3}$$

and

$$E = b_1 + b_2 \, Log\eta + b_3 \, AC + b_4 \, VTM, \tag{4}$$

where

E = Elastic modulus (GPa),

P = Penetration (1/10 mm),

η = Kinematic Viscosity (Cst)

AC = Asphalt Content (percent), and

VTM = Voids-in-the-Total-Mix (percent).

Parameters a_i's and b_i's are model parameters determined from following a multi-variant best-fit process.

The above general equations were applied to the data corresponding to individual mixes, as well as to those corresponding to combined mixtures. Seven scenarios were considered:

1)   "Combined" — all data from El Paso and Austin mixtures

2)   "Austin"   — all data from Austin mixture

3)   "El Paso" — all data from El Paso mixture

4)   "Austin, 5% AC" — data corresponding to 5% AC content of Austin mixture

5)   "El Paso, 5% AC" — data corresponding to 5% AC content of El Paso mixture

6)   "Austin, 5% VTM" — data corresponding to 5% VTM of Austin mixture

7)   "El Paso, 5% VTM" — data corresponding to 5% VTM of El Paso mixture

Tables 1 and 2 contain the regression coefficients as well as the parameters of the goodness of fit (i.e. the correlation coefficient (R^2), the root mean square error (Root MSE), and the F-value) for penetration and viscosity, respectively.

Initially the intent was to develop general relationships that could be used under any condition. These analyses clearly show that a broad generalization may not be possible. The statistical parameters of the combined mixtures do not show sufficient power (i.e., $R^2 = 0.58$ for the penetration, and $R^2 = 0.65$ for the viscosity). With regards to individual mixtures, the statistical parameters of the Austin mixture also showed an unexpectedly low power (i.e., $R^2 = 0.53$ for the penetration, and $R^2 = 0.56$ for the viscosity); whereas, those of the El Paso mixtures presented a satisfactory goodness of fit (i.e., $R^2 = 0.88$ for the penetration and viscosity).

Since the asphalt content of most of the field mix designs average about 5 percent, additional models, considering only those specimens having 5% AC contents, were developed. In this case, the goodness of the fit substantially improved. The R^2 values for the Austin and El Paso mixtures increased to better than 0.7, and 0.95, respectively.

When the analyses were performed on the subset of data with a 5 percent VTM, the goodness of the fit also significantly improved for El Paso mixture, but not for the Austin mix. The reason for this matter is under investigation.

Equations 3 and 4 were then algebraically solved to determine the penetration and kinematic viscosity of the asphalt. To assess the quality of the prediction models, the predicted rheological values obtained from using Equations 3 and 4 were compared with the measured values. A histogram representing the percent error between the calculated and actual values was developed for each of the seven scenarios itemized above. Percent error is defined as the ratio of the absolute difference between actual and predicted values to the actual value, expressed as a percentage. The histograms are summarized in Tables 1 and 2. For the combined models, only about 30 to 40 percent of the data obtained in this study could be estimated within 30 percent error, indicating that the likelihood of developing a relationship that is applicable to all mixes is small.

From the statistical parameters and the cumulative percent errors reported in Table 1 and 2, it can be seen that when data related to a 5-percent AC content were used, the models yielded mixed results. In the case of the Austin mix, about 43 percent of the penetration results were predicted within 20 error. In the case of the model developed using El Paso data, almost 100 percent of the penetration values were predicted within 20 percent error. The models designed to determine the kinematic viscosity of the Austin and El Paso mixes exhibited more or less similar strength. From Table 2, about 43 percent of the data obtained from using the model considering Austin mix data alone were predicted within less than 20 percent error. Similarly, in the case of the model using El Paso data, approximately 87 percent of the data were predicted within less than 20 percent error.

This feasibility study shows a mixed trend. The methodology works extreme well for the El Paso mix. On the other hand, the models developed for Austin mix do not yield a strong relationship. An intense study is under way to determine the reason for such results.

Estimation of Asphalt Grade Using Prediction Models - Practical Application

The models discussed in the previous section can be presented in a more practical way. Practically speaking, the asphalt grade of a particular material, and not the exact value of its penetration or viscosity, is of primary interest. The models described above can be used for the purpose of determining asphalt grade. Envelops distinguishing the asphalt grades were established using the specifications set by ASTM D3381-83. These specifications are shown in Table 3. Using the specification limits, prediction charts, assuming a 5-percent AC content, were prepared for the El Paso mixture.

For each of the boundary values (penetration values), modulus values at 3 percent, 5 percent, and 7 percent VTM levels were calculated using Equation 3. Figure 6 contains charts that differentiate the asphalt grade of the El Paso mix from that of the Austin mix. The modulus decreases with an increase in the VTM. Similarly, the slope of the fitted lines (i.e., the rate of increase in modulus) is found to be uniform with asphalt grade.

From Figure 5, the asphalt grade of mixes similar to that of the El Paso mix can be determined without conducting the Abson recovery test, provided that the modulus and the VTM of the mix are known. Similar charts could readily be developed for kinematic viscosity.

An attempt was made to use the chart shown in Figure 5 to validate its applicability. Cores from in-service pavement at three sites (San Angelo, TX; El Paso, TX (different than that used in developing model) ; and Childress, TX) visited for other research purposes were used in this case study. Two cores from each site were selected. The elastic modulus of the mixture was measured on the intact cores. The binder was then recovered to determine the viscosity, penetration and AC content.

The measured moduli as well as the measured and predicted penetrations and viscosities of each mixture are included in Table 4. To estimate the penetration and viscosity Equations 3 and 4 with the regression coefficients related to the El Paso mix (see row 4 of Tables 1 and 2) were used. Practically speaking, the calculated and predicted values are not that far off, given that none of the mixes were used to develop the model.

Shown in Figure 5, is the asphalt grade predicted for the three binders. Except for the El Paso mix, where the grade is marginally missed, the others are predicted reasonably well.

In summary, the models using the elastic modulus could possibly be used to get an estimate of the rheological parameters. The prediction charts like the one shown in Figure 5 may be used to estimate the grade of the asphalt used in the mix without opting for the Abson recovery.

Conclusions

A feasibility study based on an analysis of two different mixes was performed. Specimens were aged in an oven set at 85°C for 0, 1, 2, 7, and 28 days. An ultrasonic device was used to measure the elastic moduli of the specimens. The asphalt binder contained in the specimens was extracted and recovered to measure the specimens' rheological parameters.

Analyses were conducted to identify the mix parameters that best correlate to modulus. Based on the correlation among the parameters, models were developed for predicting the penetration and the kinematic viscosity using the elastic modulus.

Using these models along with ASTM specifications for different grades of asphalt, prediction charts were generated to estimate the asphalt grade of materials knowing their moduli.

Based on the results of this study, the following conclusions were drawn:

1. The use of wave propagation techniques can be extended to predict rheological parameters, thereby avoiding Abson recovery. However, more work is needed to refine this methodology and to fully understand the process.

2. For a given AC content and VTM, a linear relationship exists between the modulus and logarithm of penetration (or kinematic viscosity).

3. Elastic modulus is affected by both the asphalt content and the VTM of a mix. However, the effects of VTM on modulus are more prominent than those on the asphalt content of a mix.

4. The models developed appeared to be mix-specific; that is, they should be calibrated for a given mix.

5. Practically speaking, when the asphalt content ad the VTM are known, models based on elastic modulus of mixes can be used to estimate asphalt grade.

Acknowledgement

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Table 1 - Fit Parameters Relating Elastic Modulus to Penetration, Asphalt Content and VTM of Specimens Tested

Mix	Regression Parameters				Fit Quality			Cumulative percent error		
	a_1	a_2	a_3	a_4	R^2	Root MSE	F-value	10	20	30
Combined	67846	-9006	-1777	-1795	0.58	2770	37	11	20	29
Austin	57806	-9961	-377	-1154	0.53	2307	14	15	35	45
El Paso	99013	-25070	-2139	-2286	0.88	1758	97	41	81	95
Austin, 5 % AC	64164	-13017	-	-1761	0.70	2433	13	21	43	50
El Paso, 5 % AC	88704	-23302	-	-2813	0.97	1039	184	60	100	100
Austin, 5 % VTM	41255	-6363	978	-	0.27	2045	2	17	17	33
El Paso, 5 % VTM	94755	-26000	-3307	-	0.91	1561	53	43	93	100

* See Equation 3

Table 2 -   Fit Parameters Relating Elastic Modulus to Kinematic Viscosity, Asphalt Content and VTM of Specimens Tested.

Mix	Regression Parameters				Fit Quality			Cumulative percent error		
	b_1	b_2	b_3	b_4	R^2	Root MSE	F-value	10	20	30
Combined	29938	8798	-1838	-1766	0.65	2553	48	12	21	37
Austin	21963	7455	-401	-998	0.56	2249	15	18	28	43
El Paso	8759	18947	-2572	-2210	0.88	1746	98	7	14	31
Austin, 5 % AC	20251	8642	-	-1546	0.77	2151	18	29	43	57
El Paso, 5 % AC	-6593	21099	-	-2806	0.96	1127	155	53	87	100
Austin, 5 % VTM	19519	4848	769	-	0.25	2084	2	50	58	67
El Paso, 5 % VTM	262	19573	-3472	-	0.90	1668	45	29	71	93

* See Equation 4

Table 3 -   Relationship between Viscosity Grade and Rheological Parameters of AC based on Original Asphalt (From ASTM D3381-83).

Viscosity Grade	AC-10	AC-20	AC-30	AC-40
Kinematic viscosity,Cst	250	300	350	400
Penetration,1/10 mm, min.	80	60	50	40

Table 4 - Comparison of Predicted and Measured Rheological Parameters at Several Sites

ID	Site	Mix Properties			Penetration (1/10mm)		Kinematic Viscosity (cSt)		Asphalt Grade	
		Asphalt Content (%)	VTM (%)	Modulus (GPa)	Measured	Predicted	Measured	Predicted	Measured	Predicted
1	El Paso	5.8	3.5	39.7	20	23	641	674	AC-40	AC-30
2	Childress	4.3	8.2	28.9	15	11	779	401	AC-40	AC-40
3	San Angelo	4.8	5.5	44.5	12	18	772	1115	AC-40	AC-40
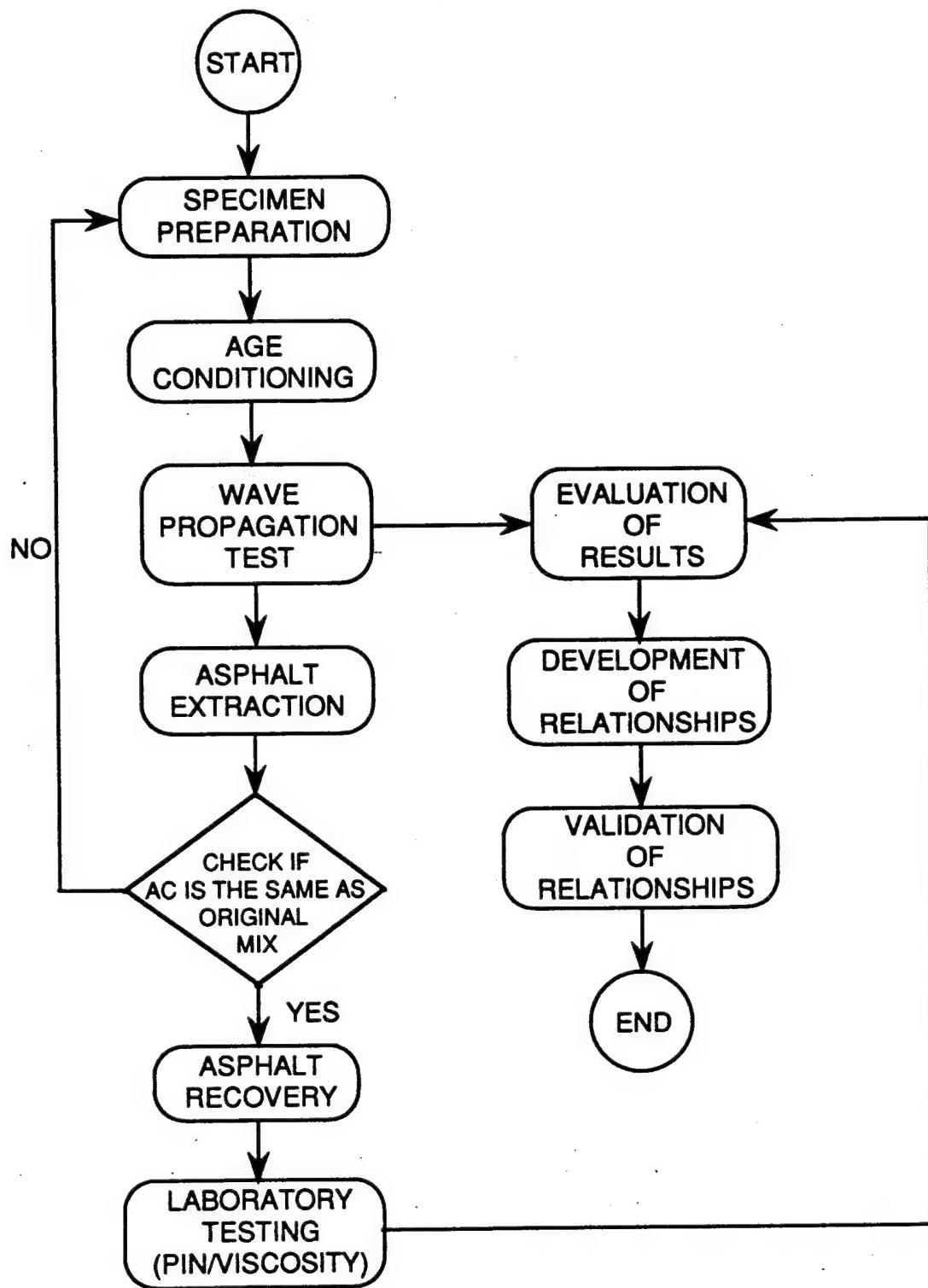
Figure 1 - Flow Chart of Research Activities
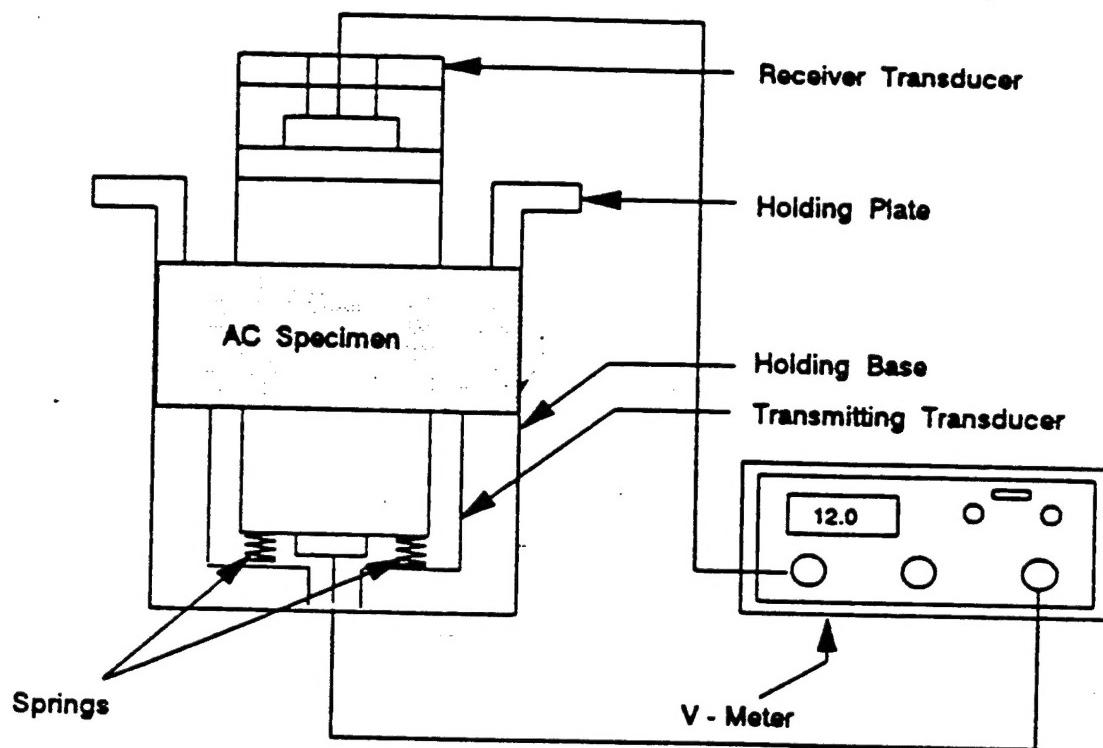
Figure 2 - Laboratory Set-up Used in wave Propagation Tests
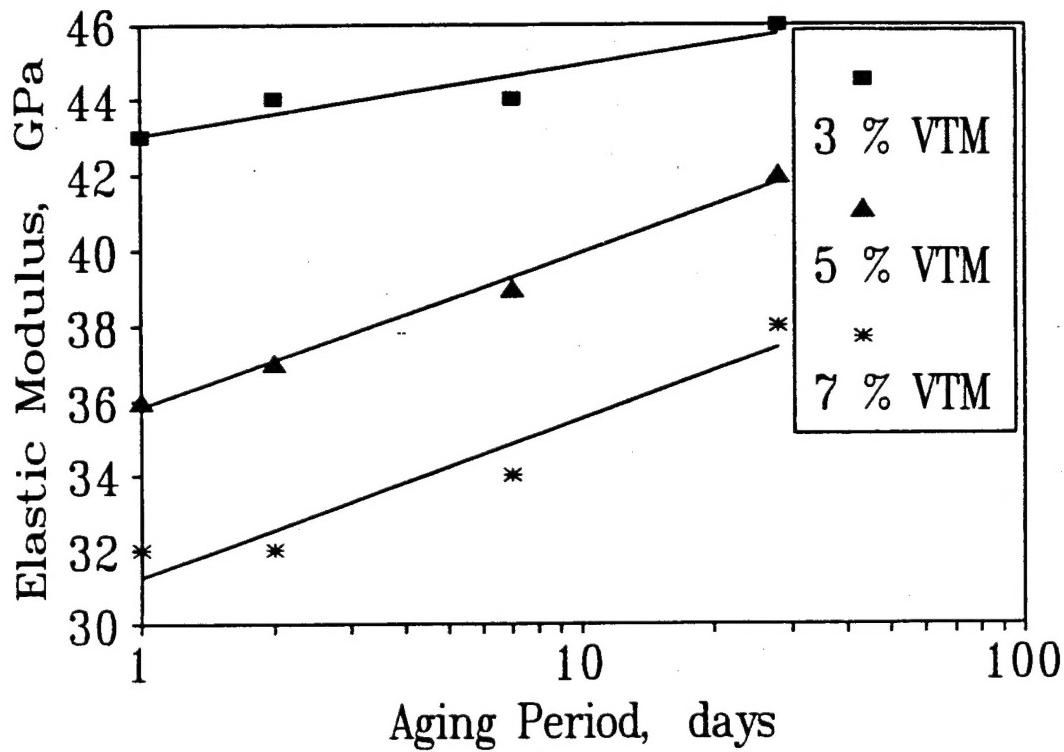
Figure 3 - Typical Variation in Modulus with Aging Period for El Paso Mix
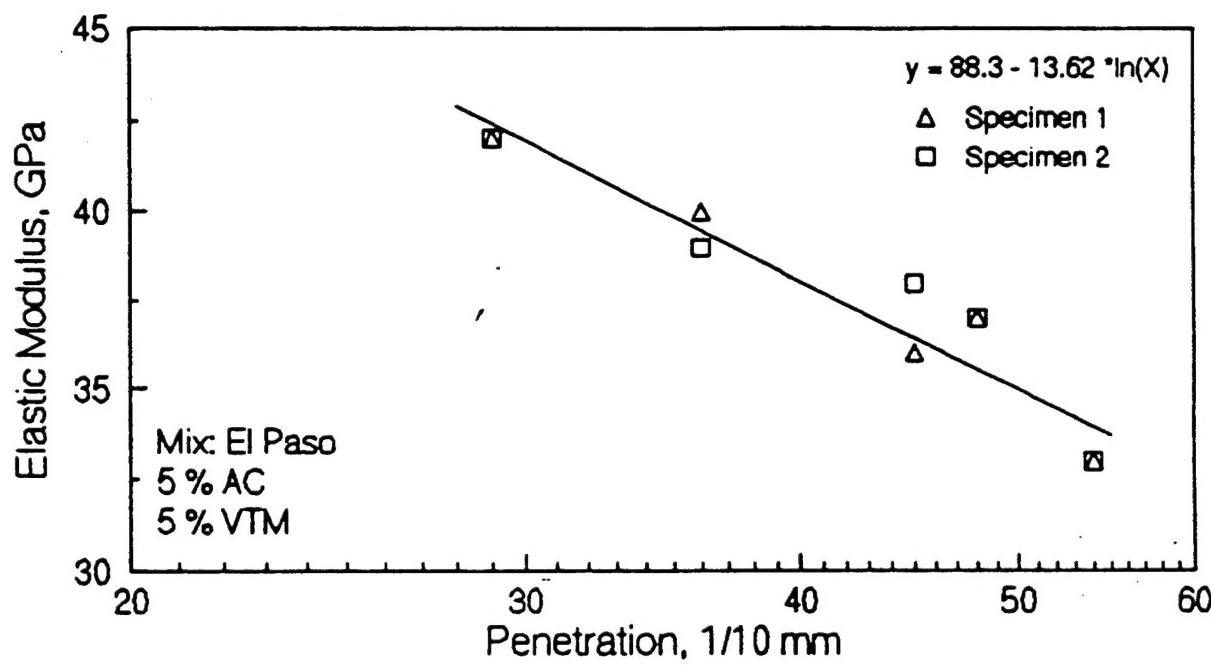
a) Penetration
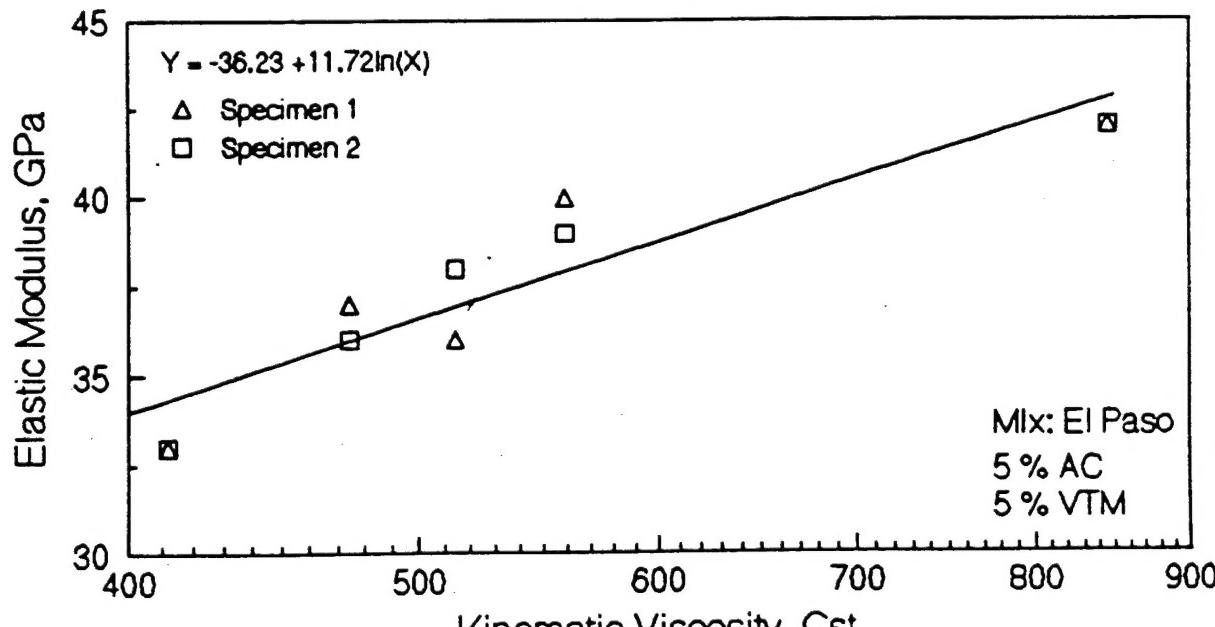
b) Kinematic Viscosity

Figure 4 - Typical Variation in Elastic Modulus of Mix with Rheological Parameters of Binder
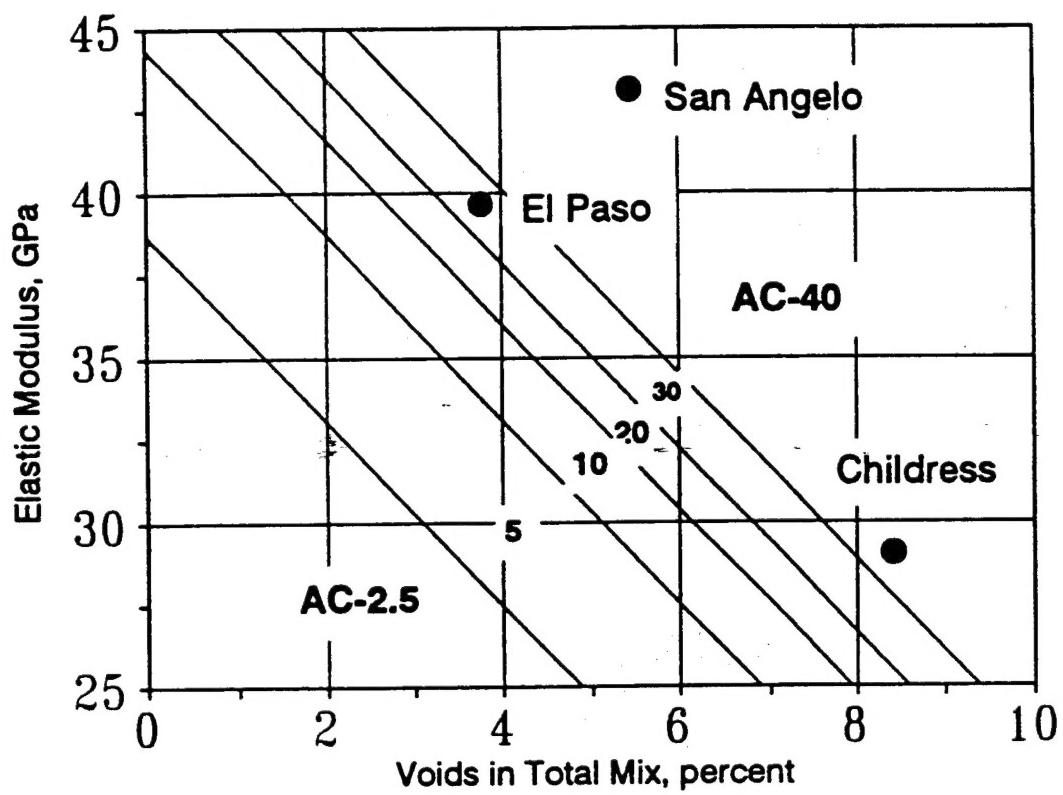
Figure 5 -   Prediction Charts for Estimating Asphalt Grafe of Binder from Elastic modulus of Mix